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The Measurement of the Smoke Leakage of Door Assemblies During Standard Fire Exposures

Leonard Y. Cooper

Center for Fire Research
National Engineering Laboratory
National Bureau of Standards
U.S. Department of Commerce
Washington, D.C. 20234

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Final Report

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The Occupational Safety and Health Administration (OSHA)
U.S. Department of Labor
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U.S. DEPARTMENT OF COMMERCE, Philip M. Klutznick, *Secretary*

Luther H. Hodges, Jr., *Deputy Secretary*
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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

PREFACE

This report on smoke leakage of door assemblies is one product of an ongoing joint research program of the Occupational Safety and Health Administration (OSHA) of the Department of Labor and the National Bureau of Standards (NBS), Center for Fire Research. The program is entitled: Key Elements of Emergency Escape Requirements for Employees in Workspaces Under OSHA Jurisdiction. Other ongoing areas of research presently included in this program are: Estimating safe available egress times for workspaces subsequent to the ignition of hazardous fires; the relation of building design and human factors to emergency evacuation of workspaces; and studies of building smoke control by means of open stairwell-sprinkler systems.

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THE MEASUREMENT OF THE SMOKE LEAKAGE OF DOOR ASSEMBLIES DURING STANDARD FIRE EXPOSURES

Leonard Y. Cooper

Abstract

A basis for relating overall intrabuilding smoke migration dynamics to high temperature, door assembly smoke leakage measurements is formulated. The results of applying the tentative, high temperature, ISO test method DP 5925 Part 3, which was developed to measure smoke leakage of door assemblies during the course of a standard fire endurance test, are reported. A critical analysis reveals that the basic objective of the method is limited in its utility in the sense that fire scenarios in high-rise buildings may not be adequately simulated. Consistent with the above-mentioned experimental results, troublesome theoretical problems with the test method and its procedures are identified. These lead to a conclusion that the test method as written is generally unreliable. An alternate test concept which removes the above-mentioned DP 5925 Part 3 limitation and all of its problems is described and its development is advocated.

Key words: Building fires; compartment fires; doors; egress; fire tests; high-rise buildings; leakage; life safety; smoke; smoke movement; stack effects; test methods.

1. INTRODUCTION

1.1 The Ability of Building Occupants to Achieve Safe Egress or Refuge

Relative to the threat of fire in occupied buildings, life safety can be measured by the ability of building occupants to achieve safe egress (or safe refuge) subsequent to a potentially hazardous ignition. The overall safe egress capability of occupants is dependent on two basic elements; namely, the time available for safe egress (i.e., the length of time subsequent to fire detection and prior to the onset of untenable conditions), and the time required for safe egress.

Safe available egress time is basically a function of the building design, including all active and passive fire protection systems, and the contained fuel loads which are characteristic of the building occupancy. Required egress time is a function of the physical nature of the egress paths, of the occupant density distribution, and of the physiological and psychological characteristics of the occupants. An excess of available

egress time over required egress time would generally indicate a safe condition vis-a-vis life safety in fires. An excess of required over available egress time would indicate a hazardous condition.

If one follows the above approach, it is evident that estimates of the available and required egress times are required for an analysis of life safety. This work addresses itself to a specific aspect of building design which impacts most heavily on the safe available egress time part of the "equation"; namely, the smoke leakage characteristics of building partition penetrations during fully developed fire exposures. The closed door assembly is taken here as the prototype of such partition penetrations. It should, however, be stressed at the outset that the ideas developed in this work would be totally applicable to arbitrary leakage paths of interest which may be characteristic to any particular wall or floor construction practice.

1.2 The Effect of Compartmentation on the Phenomenon of Smoke Migration

Depending on a given fire scenario in which hazardous conditions develop and in which partial or total building evacuation is required, the actual paths of occupant egress can pass through a variety of different building spaces. These spaces will generally become untenable at different times. Furthermore, the onset of untenability in a given space is likely to result from the spread of the potentially hot, toxic, and/or obscuring products of combustion (smoke). And the significant physical mechanisms which govern this smoke spread can vary from one space to the next.

Compartmentation has been classically used to impede the spread of fires from one space to another. Thus by proper and proven construction practice one can anticipate containment of a fire within a given compartment space of fire origin for a time interval of, for example, two or more hours. Such compartmentation constructions will not necessarily abate the spread of smoke to any significant degree. Nevertheless, compartmentation remains a convenient and useful concept for the study of smoke spread phenomenology and for estimating the onset of untenable conditions. Once smoke has passed from a compartment of fire origin, through penetrations (e.g., leaks in a doorway assembly) in its barriers, and into an adjacent compartment, new and different primary physical mechanisms of smoke spread can come into play. In short, smoke compartmentation can be the major factor in the switchover from one dominant smoke spread mechanism on one side of a barrier to a different mechanism on the other.

As a first approximation it is useful to identify two basic types of smoke migration mechanisms. One of these would be associated with a compartment of fire origin, and the other with all other parts of the building. Because of relatively high smoke temperatures, buoyancy effects are likely to dominate the dynamics of the smoke migration in the compartment

of fire origin. Taking account of these effects, Cooper [1][1] has begun to develop a technique for estimating available egress time within such compartments of fire origin (which can include "freely connected" multiple spaces). Assuming a limited rate of leakage into adjacent compartments and anticipating rapid mixing and cooling of the smoke upon entry therein, suggests the second, a "tracer gas" migration type of mechanism for the smoke's continued transport throughout the building. In particular, one would expect that continued migration and dilution of "cold" smoke outside of a compartment of fire origin could be studied by dynamic building infiltration and ventilation models, i.e., by assuming that continued intrabuilding smoke movement and dilution is driven by active forced ventilation systems and, if appropriate, by building stack effects.

Note that the definition of compartmentation in the present, smoke migration, context is keyed to the above words, "assuming a limited rate of leakage into adjacent compartments." The problem of quantifying such a definition so that a particular enclosure of building space can be rated as a bona fide compartment in the above sense for some length of time following ignition will not be addressed here.

1.3 The Utility of High Temperature Smoke Leakage Measurements

The compartment of fire origin is the source of smoke for the rest of the building. From the above discussion it is evident that a dynamic analysis of the development of untenable conditions outside of this compartment would require estimates of the rate of leakage across various paths in its bounding partitions. For example, if a door assembly provides the major leakage path, then its rate of leakage while being exposed to a characteristic threatening fire would provide the necessary input data for such an analysis. For life safety evaluation and design purposes, the leakage data of such a door assembly during the course of a standard fire endurance test would be useful in this regard. And such door assembly leakage data need not be used only for the relatively sophisticated task of estimating the actual time to untenability in the various building spaces. Indeed, it is likely that such quantitative leakage data would also be useful in a simple ranking of door assemblies relative to their smoke stopping capabilities. For example, some practical utility could be potentially extracted from the notion that: the "tighter" the door assembly, the greater the available egress time throughout the building (outside the fire compartment). A quantitative measure of door assembly "tightness" is required to invoke even this simple idea.

Presently accepted methods for measuring the response of door assemblies to fully developed fire exposure conditions are typified by ASTM E 152/NFPA 252, Fire Tests of Door Assemblies. Following that procedure, door assemblies are tested and rated for ability to stay in place when exposed to fire (and to a water hose stream) until a limiting gap size

[1]Numbers in brackets refer to literature references listed at the end of this report.

is formed. The test does not require simulation of any particular real fire, cross-door pressure differential, and it does not measure the air (or gas or smoke) flow across the door assembly. Therefore, having received a rating by virtue of its performance during this test procedure, the leakage characteristics of a particular door assembly are still unknown. If leakage characteristics of door assemblies are to be measured then an alternate or revised test method is clearly required.

1.4 An Overview of This Investigation

It was the original objective of the present investigation to measure the leakage rates of various common, (ASTM E 152) rated door assemblies during the course of standard fire exposures, and, ultimately, to place the results of these measurements into the perspective of the above discussion on successful egress from buildings. The vehicle chosen to perform the high temperature leakage measurement was the proposed International Organization for Standardization (ISO) test method ISO/TC 92/WG 3 N 203 - DP 5925 Fire Tests, Smoke Control Door Assemblies Part 3, High Temperature Test. Although this test method was still under development at the time of this choice, it was the only test method available for the task at hand. The test method was implemented and was found to have both limitations and significant basic shortcomings. The investigation eventually focused in on an analysis of these shortcomings. Finally, an alternate test concept which removes the limitations and shortcomings of the present high temperature DP 5925 Part 3 test method was formulated. The details of all of this are reported in the sections to follow.

2. APPLYING THE HIGH TEMPERATURE TEST METHOD

2.1 The Proposed ISO Test Method for Measuring the Smoke Leakage of Door Assemblies During Standard Fire Exposures

The ISO Technical Committee ISO/TC 92, Fire Tests for Buildings and Structures, is preparing three different methods for testing the leakage characteristics of door assemblies. These are all documented under the title "DP 5925 Fire Tests, Smoke Control Door Assemblies." Each of the methods is being designed to test leakage under a different simulated condition of building smoke and fire exposure. The tests are to be identified as Part 1 - Ambient Temperature Test; Part 2 - Medium Temperature Test; and Part 3 - High Temperature Test. An introductory document which discusses the relevance of these test methods is identified as "DP 5925 Part 0 - Commentary." To date, Part 0 and only two of the three test methods, Parts 1 and 3, have been formulated to the point of being documented. The tentative test method of interest here is Part 3. A copy of the most recently revised version of this is included in appendix A.

The basic idea of the high temperature test is rather simple. A sketch of the test setup is included in figure 1 of the appendix A document.

A door assembly to be evaluated is mounted in a wall assembly. This is integrated in a wall furnace as if the door assembly were to receive a standard fire resistance rating, for example, by ISO 3008 or ASTM E 152. A large collection enclosure covers the entire unexposed portion of the door assembly. A circular opening of diameter 30 cm (11.8 in) penetrates the enclosure opposite the door surface. The enclosure is carefully attached to the wall which contains the door assembly in a manner to minimize the leakage of gases from the enclosure through these attachment points. During the course of a test the furnace gases pass through the door assembly leakage paths under evaluation, into the enclosure, and out through the circular duct-like opening. The leaking furnace gases simulate the smoke laden gases that would leak across the assembly during an actual threatening fire scenario. Velocity measurements of the enclosure outflow gases are made at one point on the axis of the opening. Assuming quasi-steady flow and uniform gas velocities at a section of the outflow duct, conservation of mass is invoked and the velocity measurement is used to deduce a time varying rate of door assembly leakage.

So as not to continuously subject the unexposed surface of the door assembly to an unrealistic environment due to trapped hot furnace gases, an upper and lower vent (water sealed to prevent spurious leakage) is added to the enclosure structure. These vents are left open for 4-minute intervals during the course of the test procedure. Following every one of these 4-minute intervals the vents are closed for 1 minute during which time the quasi-steady flow condition described above presumably establishes itself. At the end of each 1-minute interval the above-mentioned outflow velocity is recorded, the vents are then opened, and the next 4-minute open vent interval is initiated.

The driving force for smoke (furnace gas) leakage during the high temperature exposure simulation is the distributed pressure difference across the door assembly, i.e., from inside to outside of the furnace. This must be specified in the test method. Toward this end the procedure specifies that the furnace pressure be controlled to maintain a zero pressure differential at the door sill. Taking the door height to be H, and the absolute temperature of the furnace at time t into the test to be $T_f(t)$, the effective result of this specification is a positive pressure differential across the door assembly which linearly increases the elevation, with rising from $\Delta P = 0$ at the sill to $\Delta P \simeq 11.5\ (H/\text{meters})[1 - T_{amb}/T_f(t)]$ pascals at the top of the door.

Other than the usual data on furnace performance, the measurements called for in the test procedure are limited to the pressure difference across the door at its sill, and the velocity and temperature of the gases at the axis of the circular outflow port of the enclosure.

2.2 The Original Objective of This Investigation

As discussed in section 1.3 the original objective of this investigation was to subject several different door assemblies to the high temperature ISO test method described

above. The plan was to build an enclosure and to test four different door assemblies of the types tabulated below.

Tests to be Conducted	Door Type	UL Classification	Glass Size
2	UL Classified Hollow Metal Type Stiffner Design	1-1/2 hr (B)	No Glass
1	UL Classified Hollow Metal Type Stiffner Design	1-1/2 hr (B)	100 sq in Vision Light
1	UL Classified Hollow Metal Type Stiffner Design	3/4 hr (C)	30 by 40 in Vision Light
1	UL Classified Kalemin Type	1 hr (B)	No Glass

An initial "shakedown" test was alloted for the first of the door types listed in this table. Thus, a total of five different high temperature door assembly tests were planned, where the first and second of these would be done on a 1-1/2 (B) UL classified hollow metal type door assembly of Stiffner design and with no glass.

The tests were to be run at the Underwriters Laboratories (UL) in Northbrook, Illinois.

2.3 An Overview of the Results of Applying the Test Method

2.3.1 The First Test

2.3.1.1 Description of the Test

In accord with the above objectives the first test was run on the hollow metal door in accordance with the DP 5925 Part 3 test procedure. Besides the measurements called for in the procedure, data was also acquired on the temperature and horizontal displacement of the unexposed door surface, the air temperature in the enclosure near the upper vent, and the temperature at a point on the outside surface of the enclosure.

All channels of data were recorded on paper tape every 30 seconds during the course of the test. The enclosure vents were designed to be operated by a hydraulic system which would be activated manually.

The prescribed 4-minute open; 1-minute closed vent sequence was followed initially, but later into the test the closed vent intervals were increased to 1-1/2 and then 2 minutes. The test was terminated after approximately 55 minutes because of a breakdown of the hydraulic vent control.

2.3.1.2 Results

It is sufficient for the purpose of the present report to briefly describe the significant results of the first test at UL. The results of a second, similar test will be presented in considerably more detail in section 2.3.2.

The major measured results were related to the center line outflow duct gas velocities as measured toward the end of closed vent time intervals. With regard to this it appeared that these velocities had not reached quasi-steady values as would be required if the fundamental philosophy of the test method is to be valid.

Besides the above-measured result there was also a significant visually observed result, namely, between 1 and 1-1/2 minutes following vent closure a stratified smoke layer started to flow out of the upper part of the outflow duct. (The painted surfaces of the door and frame were the likely sources of this smoke.) This continued until the end of the closed vent time interval. It was noteworthy that the above-mentioned measured values of outflow velocities approached inordinately small values (the order of tens of feet per minute-- sometimes smaller) compared to the visually observed velocities (of the order of hundreds of feet per minute) in this smoke layer.

As a point of information, toward the end of the closed vent time intervals and toward the end of the test the recorded temperatures of fire gas in the upper part of the enclosure approached 200°F (93°C). Also, at these later times the unexposed door surface temperature reached the order of 750°F (399°C).

2.3.1.3 Reflecting on the Results

The above results clearly called for some reflection regarding the likely overall nature of the transient gas flows within and through the enclosure subsequent to the initiation of the closed vent test intervals. This resulted in a conjecture that the phenomena in question were analogous to those produced by a heat source in a ventilated enclosure. In this analogy the outflow opening in the present experimental setup would correspond to the enclosure ventilation opening. The hot leakage furnace gases and the hot unexposed surface of the door, both of which must have been generating buoyant plumes near the door surface in the present experimental setup, would correspond to the enclosure heat source. Just as would occur upon switching on the heat source in the ventilated enclosure, it was therefore conjectured that upon closing the vents during the present experimental procedure these latter plumes would result in a filling of the enclosure with an upper, growing layer of hot gases. Eventually the nature of the steady state would be one where the flow of gases at the circular ventilation opening would be outward (hot gases) at the upper portion of this section, inward (cool ambient air) at the bottom portion of the section, and with a neutral plane (zero velocity) somewhere near the elevation of the outflow duct axis.

If the above conjectured phenomenology does indeed occur while carrying out the test procedure and/or if steady-state flows do not establish themselves fairly rapidly, say, within a minute or two following vent closing, then it is evident that there would be serious questions about the basic validity of the test method.

2.3.1.4 Conclusions of the First Test

In view of all the above it was concluded that at least one further test, identical to the first but with more instrumentation and data collection, should be carried out. Note that this conclusion was compatible with the original test plan which called for two tests on the same hollow core steel door design. More important, however, it was compatible with a new and clear requirement that the above questions raised by the first test be answered.

Another conclusion of the test was that a careful analysis of the phenomena occurring during the test procedure should be carried out. After a review of the second UL door test in the remainder of this section, a presentation of the results of this analysis-- basically an in-depth critique of the proposed DP 5925 high temperature test method-- will follow in section 3.

2.3.2 The Second Test

2.3.2.1 Description of the Test

A second test was run at UL which was essentially identical to the first except for greatly improved instrumentation.

Figures 1 and 2 indicate the locations of most of the thermocouples. Most of these were located within the enclosure so that the transient development of the gas temperature distribution could be studied, e.g., for the purpose of establishing the potential compatibility of data with the conjectured stratification phenomenology discussed earlier. Those few thermocouples which were located in the outflow duct were to provide an indication of the validity of the cool lower inflow — hot upper outflow velocity distribution which was conjectured to occur during latter parts of closed vent time intervals.

Figure 3 indicates the locations where pressure differentials were measured. One of the main reasons for these, i.e., ΔP_1 and ΔP_5, was to provide an indication of the variation in time and in elevation of the enclosure-to-ambient pressure differential, e.g., for the purpose of establishing the compatibility of data with the conjectured quasi-steady position (near the outlet duct axis) of the enclosure-to-ambient neutral plane.

All data channels were scanned and recorded on magnetic tape once every 5 seconds.

For the first 40 minutes of the test the 4-minute open; 1-minute closed vent sequence was maintained. After this time the closed vent interval was increased to 2 minutes. The test was terminated after approximately 80 minutes at which time the vents became stuck in the closed position.

2.3.2.2 Results

The results of the second test generally corroborated those of the first test. Additional insight into the flow phenomena was provided, however, by the more detailed instrumentation capability.

The pressure differential data and the outflow velocity data which cover three representative closed vent time intervals, 840-900 seconds, 2400-2520 seconds, and 4020-4140 seconds, are presented in figures 4-5, 6-7, and 8-9, respectively. The temperature history at the three thermocouples located in the throat of the outflow venturi for the latter of these closed vent intervals is presented in figure 10. The enclosure temperature distribution at seven different, equal spaced times during this time interval is presented in figure 11. The temperature values plotted in this latter figure are an appropriate average of the temperatures measured by thermocouples located within the enclosure at identical elevations.

All of the above data support the general conjecture, briefly presented above in paragraph 2.3.1.3 regarding the gas flows within and through the enclosure. The analysis of these flow phenomena to be presented in the next section will place this data into proper perspective. For the present, the following brief observations will suffice:

Figures 4, 6 and 8 indicate that quasi-steady enclosure-to-ambient pressure differentials ΔP_1 (top of door) and ΔP_5 (bottom of door) were attained within 1-2 minutes following vent closure. From the fact that these quasi-steady ΔP_1 and ΔP_5 values are of different sign, it is also evident that in each of these three closed vent sequences a neutral plane (i.e., the elevation where $\Delta P = 0$) must have been formed somewhere between the top and bottom of the door. From the fact that ΔP_1 consistently approaches the approximate value $-\Delta P_5$, one also learns that the quasi-steady positions of these neutral planes were near the mid-door elevation (i.e., near the elevation of the outflow duct axis).

If the neutral plane elevation is in the vicinity of the duct axis, then the net outflow through the duct can change significantly with relatively small variations (e.g., a few tenths of a duct diameter) in this neutral plane elevation. (This fact will be substantiated below in the analysis of section 3.3.3.) Accordingly, when the neutral plane reaches the vicinity of its quasi-steady elevation, say, to within a few inches, the actual net flow through the duct will still deviate significantly from its quasi-steady value. The lag between the establishment of the quasi-steady neutral plane position

(i.e., quasi-steady ΔP_1 and ΔP_5) and the establishment of quasi-steady net outflow is indicated by comparisons of the velocity histories of figures 5, 7 and 9 and the ΔP_1 and ΔP_5 histories of figures 4, 6 and 8. For example, whereas figure 4 indicates that quasi-steady ΔP's are attained by 1 minute following vent closure it is not clear from the data of figure 5 that a quasi-steady duct axis velocity is at hand at this time. As another example, figure 8 indicates that near-steady ΔP's are attained by 1 minute following vent closure. However, the corresponding data of figure 9 suggests that even at 2 minutes following vent closure, quasi-steady velocities in the duct cross section may not have been attained. The enclosure gas temperature histories of figure 11 also indicate that full quasi-steady conditions had not yet occurred by the end of the 4013-4132-second test interval. Finally, the duct temperature data of figure 10 strongly support the contention that, even as quasi-steady pressure conditions begin to be established, a highly transient lower inflow of cool ambient air and upper outflow of hot enclosure gases are in evidence at the venturi throat cross section.

2.3.2.3 Overall Conclusions of the Two Tests

The results of the two tests at UL indicated that the proposed high temperature test is not likely to provide the door assembly leakage measurement for which it was designed. As will be seen, the analysis to follow in section 3 strongly supports this result. Because of this it was concluded that the remainder of the UL test program, as delineated in paragraph 2.2, be postponed until a satisfactory alternate door assembly leakage test was developed. Such an alternate test concept is proposed below in section 4.

3. A CRITICAL ANALYSIS OF THE TEST METHOD

3.1 Preliminary Remarks

This section is devoted to a critical analysis of the proposed high temperature ISO test method DP 5925 (appendix A) for measuring smoke leakage past door assemblies. As noted in section 2.3.1.4 the need for this analysis became evident after reflecting on the unexpected results of the first UL test. The results of the analysis to follow, although compatible with the results of both the first and second UL tests, will be seen to stand independent of them.

As will be seen, the analysis reveals that the basic objective of the test method is limited in its utility in the sense that fire scenarios in high-rise buildings may not be adequately simulated. More significant, troublesome theoretical problems with the test method and its procedures are identified. The presentation to follow first discusses the test limitation. Following this is an analysis of the more basic theoretical problems.

3.2 A Limitation of the Test Method

3.2.1 The Distribution of Pressure

The basic idea of the test in question is to measure the rate of gas leakage across a subject door assembly during the course of a fire exposure which simulates a fully developed flashed-over fire. At any time during the test this leakage rate will clearly depend on the distribution of pressure difference, Δp, across the door assembly. As delineated in sections 3 and 7.2 of DP 5925 Part 3, the actual distribution modeled is the one where the pressure in the furnace (representing the room of fire origin) is controlled in such a manner as to result in a zero (0-1 pascals) Δp at the bottom of the door assembly (i.e., the neutral plane is fixed at the door sill). By maintaining a zero Δp at this level, the vertical variation in Δp is automatically determined by the then current temperature (density) of the furnace gases.

The idea of the particular pressure distribution specified in the test is that it presumably leads to conservative results in the sense that a higher leakage rate will result in the test than would occur if, say, the neutral plane (the level of zero Δp) were fixed at a level above the door sill. Indeed, for one particular door gap assumption Dekker and Haffmans [2] have estimated that almost twice as much gas would flow from the room of origin, in the case of the present Δp distribution, than in the case of a modified distribution where the neutral plane was one third of the door height up from the door sill. As it turns out, the conservative nature of this result only holds up when one considers use of the door assembly in low to moderate height buildings or in tall buildings under moderate climate conditions, and under low to moderate wind conditions.

3.2.2 Capability of the Test Method to Simulate Effects of a High-Rise Building Fire Scenario

In considering use of the door assembly in high-rise buildings, or, more directly, in buildings where the stack effect is significant, the singular pressure distribution specified by the test method no longer leads to conservative results. This becomes clear from the following considerations: The source of smoke which infiltrates a high-rise building is the room (smoke zone) of fire origin. The rate at which this source passes smoke into the overall building air supply is determined by 1) the geometry of partition penetrations (in our case, door assembly penetrations) and by 2) the distribution of Δp across these penetrations. The Δp that would exist in practice could be of the order of several tens of pascals -- several times larger than the Δp being considered in the present test method. In short, while the test method may lead to conservative estimates of smoke leakage when the door assembly was used in low buildings, it could lead to significant underestimates of smoke leakage rate when the door assembly was used in high-rise building applications. And it is precisely the "fire in the high-rise building problem" that has drawn so much attention to the general problem of smoke movement.

Before leaving this section, it is appropriate to briefly describe a typical fire which would result in a relatively high over-pressure Δp of the type referred to above. Such a scenario might look as follows: Fire breaks out in a room on a low floor in a high-rise building during cold winter climate conditions. The room flashes over and a ventilation or fuel controlled fire develops where ventilation is from broken windows on exterior walls. From this time on the fire room pressure is substantially maintained at the outside pressure. This room of fire origin is connected to adjacent rooms by partitions with relatively small penetrations, e.g. (closed) door assemblies. The pressure in these adjacent rooms is substantially at an inside pressure which is characteristic of the (low) floor under consideration. The ΔP across all these partitions is therefore maintained at levels which are of the order of magnitude of several tens of pascals, i.e., at levels which are of the order of magnitude of inside to outside stack effect, pressure differentials.

3.2.3 The Limited Utility of the Concept of a (Constant) Orifice Coefficient

In addition to the observations in the last paragraph it is timely to point out that there is no good technical basis for obtaining required "high over-pressure" results by scaling up valid "low over-pressure" data (which would presumably be acquired by following the present test method). This is the case for two reasons: 1) The ΔP distributions are qualitatively different. Thus, the leakage rate in the present test method is a result of a strongly varying vertical ΔP distribution (nominally zero at the door sill, and increasing linearly with height to the order of 10 pascals at the top of the door), whereas the high over-pressure type of loading to be simulated would be relatively uniform over the entire assembly, e.g., several tens of pascals $\pm$ the order of 10 pascals. The flow coefficient for the leakage cannot be characterized as an orifice coefficient in the usual sense. The (constant) orifice coefficient concept can be valid when the flows involved are mostly turbulent (i.e., are at relatively high Reynolds number, Re). However, for the present case of long gaps (cracks) which act like moderately long two-dimensional ducts, the flows will be of relatively small and highly varying Re. Besides that, these flows are not likely to be fully developed for much, if any, of their duct lengths. In short, flow coefficients associated with a given (narrow) door gap of interest will be strongly dependent on gap geometry and on the ΔP across the gap (or on the gap Re).

It is noteworthy that the above ΔP dependent flow coefficient phenomenon, which would be exhibited in cold gas flows as well as in hot gas flows, has been observed in the present context by Keough [3]. The added problem in the high temperature test is, of course, the fact that gap geometry is changing during the course of the test due to expansion, warpage, etc. of the door assembly.

3.2.4 Desirable Attributes of a Smoke Leakage Test Procedure

The remarks in the above paragraphs lead to the following conclusions:

Flexibility in achievable ΔP distributions would be an attractive feature of a test method for measuring leakage characteristics of partition assemblies. This flexibility should include a ΔP distribution which is reasonably uniform and of the order of 100 pascals, as well as a ΔP type of distribution characterized by a neutral plane ($\Delta P = 0$) somewhere near the door sill.

The present test method does not have the former, high pressure capability, and this is a significant limitation in the evaluation of door assemblies for high-rise building usage. This limitation could be overcome by following an alternate test concept to be discussed below in section 4.

3.3 Some Troublesome Theoretical Aspects of the Test Method

3.3.1 General Remarks

There are two basic theoretical aspects of the test method which lead to serious questions regarding its usefulness. The first of these has to do with the fact that the gas outflow from the enclosure (during the closed vent phases of the test) has two, inseparable components. One component, the one which the test sets out to measure, is the actual leakage gases. The other component, which is of no interest, and which cannot be physically separated from the first, is the result of expansion of enclosure gases due to heat transfer from the hot, unexposed surface of the door assembly under test. As will be seen, this latter expansion component can be of the same order as the former leakage component.

The second aspect has to do with the complicated nature of the steady-state flows which develop in and through the enclosure following closure of the vents. It is after this steady state is reached that the test procedure actually calls for outflow measurements[2].

In the remainder of the paragraphs under section 3.3, an analysis of the impact and implications of these two aspects of the test method is presented. At first it would appear that several seemingly influential factors may have to be directly taken account of during the course of such an analysis. A partial listing of such factors would include,

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[2]The actual test procedure does not directly call for measurement at the steady state, c.f., 7.3 Operating Procedure of DP 5925. Rather it is assumed that this steady state will occur by 1 minute following vent closing, and the procedure explicitly calls for measurement at this time. The actual time to reach steady state will be a strong function of the specific door assembly under test and the time into the test, and the indirect, 1-minute prescription for steady-state definition can lead to serious error. This is borne out by the test results of section 2, for example, where the velocity data of figure 7 suggest that an effective steady state may be at hand by 1 - 1-1/2 minutes following vent closure at 2400 seconds, and where the velocity data of figure 9 suggest that even 2 minutes following vent closure at 4200 seconds steady state may not have been reached.

for example, furnace pressure, geometry and position of the gaps in the door assembly, volume of the enclosure, and elevation and diameter of the enclosure exhaust port. As it turns out, however, there are only four factors that are, in fact, required for such an analysis, namely, the overall leakage of the door assembly (which would, of course, be a complicated and apriori unknown function of furnace pressure and gap geometry), the diameter of the exhaust port, the outer door surface temperature, and the temperature of the enclosure gases near the elevation of the exhaust port axis. At appropriate places in the discussion below, these factors will be reintroduced.

3.3.2 The Two Components of Outflow

As mentioned above, one component of the outflow gas flow rate is the actual leakage rate. It is, of course, the entire purpose of the test to measure this leakage rate. Unfortunately, there is another component to these outflow gases, which can be small or large compared to the first. This added component comes into play once the temperature on the unexposed surface of the door assembly starts to become significantly larger than the ambient temperature. Thus the expansion component will be small relative to the leakage component very early in the test, and may[3] remain relatively small for a longer period of time in the case of doors with relatively higher insulating properties. Indeed, even for uninsulated doors, and late into a test, the expansion component of the outflow may (again) be eventually masked by the leakage component if door warpage and resulting increasing gap dimensions proceed far enough along.

In general it is difficult to make apriori estimates of the relative significance of the expansion component for a given door assembly system. But an order of magnitude estimate of this flow rate is achievable. Such an estimate was obtained, and it is presented in appendix B. The result of this is plotted in figure 12. As can be seen there, for a door of dimension 1 m x 2 m and for $\Delta T = T_{surface} - T_{gas}$ of the order of hundreds of °C, the outflow due to expansion will be of the order of tens of m^3/hr. It is evident from leakage rate data of [3] and [4], for example, that such rates of outflow could completely mask the leakage phenomenon under study. In such circumstances (which are, apriori, not evident) the present test method may be totally inadequate.

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[3] The qualifier "may" is important. It is used here for the following reason: Whereas the actual expansion effect will be smaller at all times in the case of a better insulated door, the insulated door may deform in such a manner as to significantly decrease the rate of leakage as the test proceeds. Thus, in the case of well insulated doors, it may not be unusual if the ratio of expansion component to leakage component increased from zero with reasonable rapidity. Indeed it is very difficult to generalize regarding the outcome of the potentially complicated interplay of in-depth door temperature distribution, thermal deformation, and unexposed surface heat transfer which would develop during the course of a test. This interplay would be a custom feature of any specific door assembly system.

In the special case of the tests described above in section 2, and toward the end of these tests, the expansion component of the outflow is estimated from figure 12 to vary from approximately 45 m^3/hr to approximately 30 m^3/hr during the course of a 2-minute closed vent interval.

3.3.3 The Nature of the Steady State and Its Implications

3.3.3.1 An Overview

Upon closing the vents at a given time during the course of the test, the procedure is to wait until a steady state is reached, and then to measure[4] the outflow from the enclosure. By applying the principle of conservation of mass in its steady-state formulation, this measured rate of mass outflow is presumably equal to the rate at which mass leaks through the door assembly. As it turns out, a description of the nature of this steady-state is elusive. However, whatever the steady state temperature and flow fields within the enclosure, it is likely that at the time of steady state the original, pre-vent closure, ΔP distribution (and the resulting leakage flow rate) will have been significantly altered. Besides this, an additional problem may manifest itself in that a uniform slug flow description of the outflow velocity distribution at steady state may not be adequate, i.e., a single point velocity measurement may not permit a reasonable estimate of the outflow rate.

The considerations of the previous paragraphs under section 3.3.2 strongly influence the quantitative aspects of the phenomena under discussion here. Yet, the above qualitative remarks are independent of these considerations as will be clarified below. The situation will first be discussed in the absence of hot door surface, expansion phenomena. Following that, a hot door surface zero leakage scenario will be discussed. Finally, the phenomena of combined effects will be presented.

3.3.3.2 Flow Conditions During Times of Cool Door Surface Conditions

3.3.3.2.1 Flow Phenomenology Following Vent Closing

For the purpose of this paragraph we assume that the unexposed door surface is effectively at ambient temperature (i.e., the outflow from the enclosure is solely due to door leakage). This assumption will always be valid early in the test. For well insulated doors it will remain valid until later into the test.

Attention is focused on the time immediately following vent closure. The enclosure is filled with cool ambient air, and it is assumed that the Δp distribution across the

[4] See the footnote at the bottom of page 13 regarding the specification of the time of measurement (steady state).

door assembly at this instant is substantially as it was prior to vent closing[5] (i.e., the ΔP is as prescribed in the test procedure). By virtue of this ΔP distribution no leakage occurs at the horizontal door sill gap. There will, however, be leakage gases entering the enclosure in the form of hot, line jets through the vertical gaps and through the upper horizontal gap of the door assembly. The horizontal momentum of these jets is quickly diffused and masked by strong increases in upward momentum.

This upward momentum is a result of the relatively strong buoyancy forces which come into play. For the case of the vertical gaps, for example, a substantially vertical, buoyant, half-plume develops, where the plume axis is coincident with the gap itself. In this case, the flow field is analogous to the flow field in a plume formed from a vertical line source of heat (buoyancy).

The unsteady phenomena related to a buoyancy source in an enclosure which is initially at uniform gas temperature have been studied by Baines and Turner [5], Zukoski [6], Zukoski and Kubota [7] and others. The steady state for this problem, when there is a ventilation opening to the outside (as there is in the present case with the outflow venturi), has been studied by a host of other authors (e.g., Kawagoe [8], Prahl and Emmons [9], Quintiere [10], and Rockett [11]. These latter studies are mainly in the context of fires in enclosures. And indeed, the flow phenomenology of interest here is very much analogous to the flow phenomenology of fires in enclosures.

Applying the ideas developed in the above referenced studies, it is likely that the following scenario will unfold immediately following vent closure:

The plumes driven by the hot furnace gases rise upward in the enclosure, laterally entraining cool ambient air all along their height. The lateral velocity of these cool gases is relatively small compared to upward velocity in the plumes, and, away from these plumes, the gases in the enclosure remain essentially in a quiescent state. The total mass flow in the plumes increases with height. The increase is due mainly to the entrained air (i.e., the ratio of entrained air to furnace gases in the plume is relatively large). Thus the average temperature in the plume decreases with height, remaining somewhere between the temperature of the hot furnace leakage gases and the temperature of the cool ambient air. Upon reaching the top of the enclosure the plume gases rapidly spread across it in a relatively thin (compared to the height of the enclosure), hot, buoyant layer.

As time goes on, the upper, hot, plume gas layer starts to increase in thickness replacing, from above, the lower cool gases which are continuously entrained into the

[5] Upon closing of the vents there will actually be a relatively small and uniform increase in enclosure pressure. This is due to the fact that all the enclosure outflow is now through the relatively small constriction of the outflow port.

plume. A complete analysis of the phenomenon would also indicate the requirement of a net outflow from the outflow port[6]. The entire situation at early times is depicted in figure 13.

As time goes on the interface between the upper and lower layers continues to drop, soon reaching the general level of the enclosure outflow port. Whether or not the steady state is at hand is not immediately clear. As will be seen, the basic question in this regard is whether the effective position of the interface continues to drop to the bottom of the enclosure or settles in a steady state somewhere above the bottom, but below the axis of the outflow port. In order to address this question a result will first be deduced concerning the steady-state level of the enclosure-to-ambient neutral plane (i.e., concerning the level at which $P_{enclosure} = P_{ambient}$).

3.3.3.2.2 Steady State Position of the Enclosure-to-Ambient Neutral Plane — A First Estimate

A general result for the steady state position of the enclosure-to-ambient neutral plane will now be obtained. As it turns out, a direct calculation for this neutral plane position is beyond the intended scope of this analysis. The following indirect approach will be seen to yield the desired result for the enclosure outflow dynamics under review.

In figure 14 is a sketch of the enclosure, and, for a relatively late time into a closed vent phase, a vertical temperature profile for the enclosure gases (away from the plume). The uniform ambient temperature is also indicated in the figure. Corresponding to these temperature profiles are plotted the vertical ambient and enclosure pressure distributions. These latter pressure profiles are the result of vertical integration of the temperature dependent density profiles. Thus

$$P_{amb}(z) = P_{amb}(z_n) - \int_{z_n}^{z} \rho(T_{amb})\, g\, dz$$

$$P_{encl}(z) = P_{encl}(z_n) - \int_{z_n}^{z} \rho(T_{encl})\, g\, dz \qquad (1)$$

where z_n is some arbitrary reference level, and where P_{amb}, T_{amb}, P_{encl}, T_{encl} are pressures and absolute-temperature of the ambient and within the enclosure, respectively. The different possible uniformly separated P_{encl} distributions in the figure indicate the fact that with the second of eq. (1) and from the known distribution of $T_{encl}(z)$ $P_{encl}(z)$ can be computed only to within an undetermined constant, $P_{encl}(Z_n)$.

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[6] The idea of a net outflow of the enclosure gases, uniform across a section of the outflow port for some initial time following vent closure, is compatible with the figure 10 plot of the section 2 test results.

Now let z_n be the unknown position of the enclosure-to-ambient neutral plane. Thus we define z_n as the position where $P_{encl}(z_n) = P_{amb}(z_n)$. Also define

$$\Delta P_{e-a}(z) = P_{encl}(z) - P_{amb}(z) \tag{2}$$

Thus

$$\Delta P_{e-a} = g \int_{z_n}^{z} [\rho(T_{amb}) - \rho(T_{encl})] \, dz$$

$$= g\rho(T_{amb}) \int_{z_n}^{z} [(T_{encl} - T_{amb})/T_{encl}] \, dz \tag{3}$$

In this last equation and throughout this entire work all enclosure gases are taken to have the properties of air. Furthermore, a constant absolute pressure, perfect gas model for air is assumed. Thus, ρT is assumed to be a single constant at all elevations within the ambient and throughout the enclosure.

In terms of comparison between eq. (3) and the section 2 tests, recall that histories of ΔP_{e-a} measured at the top and bottom positions of the door assembly have been plotted in figures 4, 6, and 8. For the specific time 4132 seconds into the second test (figure 8) the theoretical value of the bottom ΔP_{e-a} has been computed using the measured top ΔP_{e-a} value, the measured temperature profile of figure 11, and eq. (3). The excellent agreement between the computed (-0.0150 in_w) and measured (-0.0160 in_w) ΔP_{e-a} values can be seen in figure 8.

It is noteworthy that the latter calculation also led to an estimate of the neutral plane position at the time in question. This was found to be somewhere near the outflow port axis[7].

The volume rate and mass rate of flow through the outflow port, $\dot{q}$ and $\dot{m}$, respectively, can be written as

$$\dot{q} = \int_{z_p - D/2}^{z_p + D/2} w(z) \, v(z) \, dz$$

$$\dot{m} = \int_{z_p - D/2}^{z_p + D/2} \rho_t(z) \, w(z) \, v(z) \, dz \tag{4}$$

[7] The precise estimate for the neutral plane elevation at 4132 seconds was found to be 6 inches above the outflow port axis. Anticipated experimental error does not, however, allow precision in this regard better than the order of a foot.

where D and w(z) are the height and width of the outflow port, respectively, z_p is the vertical elevation of the midheight of the outflow port, v(z) is the velocity of the flow measured positive in the enclosure-to-ambient direction, and $\rho_t(z)$ is the density of the flow-through gases. Then

$$v(z) = [2|\Delta P_{e-a}|/\rho_t(z)]^{1/2} \Delta P_{e-a}/|\Delta P_{e-a}| \tag{5}$$

and

$$\rho_t(z) = \begin{cases} \rho(T_{encl}) \text{ if } \Delta P_{e-a} > 0 \ (v > 0) \\ \\ \rho(T_{amb}) \text{ if } \Delta P_{e-a} < 0 \ (v < 0) \end{cases} \tag{6}$$

Referring to eq. (3) it is now assumed that, in the z range of interest, the maximum variation of $T_{encl}(z)$ is relatively small in magnitude compared to the minimum of $|T_{encl}(z) - T_{amb}|$. This would clearly be the case for the sketched profiles of figure 14 provided z_n was in the proximity of the axis of the outflow port, e.g., provided $|z_n - z_p| < D$. Under these conditions, $T_{encl}(z)$ under the integral of eq. (3) can be approximated by $T_{encl}(z_p)$, and ΔP_{e-a} itself can be approximated by

$$\Delta P_{e-a} = g\rho(T_{amb}) \ (z-z_n) \ [1 - T_{amb}/T_{encl}(z_p)] \tag{7}$$

The ΔP_{e-a}'s that would be formed from the P_{amb} profile and from the $P^{(1)}_{encl}$ and $P^{(2)}_{encl}$ profiles sketched in figure 14 are indicative of the anticipated validity of the fact that ΔP_{e-a} does indeed vary linearly with Z in a manner consistent with eq. (7) in the Z range of interest. The $P^{(1)}_{encl}$ profile is for z_n somewhere near the elevation of the outflow port axis, and the $P^{(2)}_{encl}$ profile is for z_n slightly below the outflow port opening.

Using the result of eq. (7) in eq. (5) the following estimate for v(z) is eventually obtained

$$v(z) = \begin{cases} \{2g[T_{encl}(z_p)/T_{amb} - 1] \ (z-z_n)\}^{1/2}; \ z-z_n > 0 \\ \\ \{2g[T_{amb}/T_{encl}(z_p) - 1] \ (z-z_n)\}^{1/2}; \ z-z_n < 0 \end{cases} \tag{8}$$

Using this last result in eq. (4), and taking the outflow port as in figure 14 to be circular in section and of diameter D, the following result is obtained for the total volume flow rate and mass flow rate through the port and out of the enclosure:

$$\dot{q}^* = \dot{q}/[(D^2/2)(gDK)^{1/2}] = \phi(\lambda) - \phi(-\lambda)\ [1/(1+K)]^{1/2}$$
$$\dot{m}^* = \dot{m}(1+K)/[\rho_{amb}(D^2/2)(gKD)^{1/2}] = \phi(\lambda) - \phi(-\lambda)\ (1+K)^{1/2} \qquad (9)$$

where

$$K = [T_{encl}(z_p)/T_{amb} - 1];\ \lambda = (z_n - z_p)/(D/2)$$

$$\phi(\lambda) = \begin{cases} \int_{-1}^{1}[(1-\zeta^2)(\zeta-\lambda)]^{1/2}\, d\zeta; & \lambda < -1 \\ \int_{-1}^{1}[(1-\zeta^2)(\zeta-\lambda)]^{1/2}\, d\zeta; & -1 \leq \lambda \leq 1 \\ 0 & ; \ 1 < \lambda \end{cases}$$

$\phi(\lambda)$ is plotted in figure 15. $\dot{q}^*$ and $\dot{m}^*$ are plotted in figure 16 as a function of λ with K as a parameter. The corresponding values for $\dot{q}^* K^{1/2}$ are plotted in figure 17. For D = 0.3 m (the diameter of the outflow port prescribed by DP 5925) the dimensional values of $\dot{q}$ are also presented in figure 17 as a function of λ with $T_{encl}(z_p)-T_{amb}$ as a parameter.

For the present purposes, these plots yield the significant results of this paragraph. For example:

If $T_{encl}(z_p)-T_{amb}$ is between 60°C and 1200°C, and the volume rate of flow from the outflow port is less than 275 m^3/hr, then the level of the neutral plane, z_n, is in the relatively narrow range

$$-2. < \lambda < 0.25 \quad \text{or} \quad z_p - D < z_n < z_p + D/8$$

3.3.3.2.3 A Refined Estimate for the Level of the Neutral Plane and Its Implications

The results of the previous paragraph indicate the possibility of a neutral plane (somewhat) below the bottom of the outflow port (i.e., $\lambda < -1.$). Under these circumstances the velocity across the entire section of the outflow port would be outward. This is clearly not possible as a steady-state configuration for the phenomenon under consideration. Indeed, if the outflow port velocity was uniformly outward at steady state, then all of the gases within the enclosure would have had to have entered therein as hot leakage gases from the furnace. Thus, a steady state with the neutral plane anywhere below the outflow port implies a bulk enclosure gas temperature which is essentially at furnace temperature[8].

[8] Steady heat transfer from enclosure gases to enclosure surfaces, and then to outside air cannot be expected to drop the temperature of these gases significantly below their original furnace levels.

From figure 17, it is clear that with the present outflow port diameter, with enclosure temperatures of the order of several hundreds of °C or greater (say $K > 1$), and for $\lambda < -1$, outflow volume flow rates will exceed 400 m^3/hr. This is inconsistent with the anticipated flow rates which are not likely to exceed 100-200 m^3/hr.

From the latter inconsistency it is now evident that a neutral plane elevation, z_n, which satisfies $z_n < z_p - D/2$ (with corresponding uniformly positive outflow velocities) must be discarded as a possible steady-state scenario in the present DP 5925 test method.

In view of the above, the following conclusions result:

In the steady state configuration the enclosure-to-ambient neutral plane must satisfy

$$-1. < \lambda < 0.25 \qquad \text{or} \qquad z_p - D/2 < z_n < z_p + D/8$$

As a result of this neutral plane position, the steady velocity of the flow in the cross section of the outflow port will be a strong function of elevation. In the lowest portion of this section there will actually be a layer of air which flows into the enclosure. It is, in fact, this cool, ambient, inflow air which (by mixing with the plumes of the hot leakage gases) would maintain steady-state enclosure temperatures at characteristic levels significantly below furnace temperatures.

Note that the above theoretical conclusions are compatible with the experimental results of section 2 and with the observations below eq. (3).

The DP 5925 procedure for estimating the volume rate of flow out of the enclosure is to measure the velocity at the outflow port axis, $v(z_p)$, and to multiply this by the area of the port. Using eqs. (8) and (9), and defining the average flow velocity through the port as $\bar{v}$, where

$$\bar{v} = 4\,\dot{q}/(\pi D^2),$$

the following experimental estimate, $\dot{q}_{est}$, for $\dot{q}$ can therefore be anticipated

$$|\dot{q}_{est}/\dot{q}| = |v(z_p)/\bar{v}| = (\pi/2)\,|\lambda|^{1/2}/|\phi(\lambda)-\phi(-\lambda)/(1+K)^{1/2}| \qquad (10)$$

Using eq. (10), $\dot{q}_{est}/\dot{q}$ has been plotted in figure 18 as a function of λ with K as a parameter. It is evident from this that the experimental estimate for $\dot{q}$ can be in significant error.

3.3.3.3 Flow Conditions Resulting From the Combined Effects of Leakage and Hot Door Surface Heat Transfer

The previous paragraphs of 3.3.3.2 developed a scenario for enclosure flow dynamics that are to be anticipated solely as a result of door assembly leakage (i.e., during test times when cool door surface conditions prevail). As it turns out, a hot door surface, zero leakage scenario would follow much the same lines.

In 3.3.3.2, line plumes of hot leakage gases were considered to be the driving mechanism for the flow. In contrast to this, for the case of a zero leakage hot door surface a purely convective type (i.e., no mass injection), two dimensional plume would be formed. This would start at the bottom of the door and rise in a boundary layer flow all along the hot door surface. The net outflow from the enclosure would be the result of enclosure gases expanding from hot door surface heat transfer. All results and figures discussed in 3.3.3.2 would be entirely relevant.

The scenario anticipated in a real, DP 5925 door assembly test would, of course, involve the combined effects of leakage driven outflow and expansion driven outflow. The actual flow dynamics would be the result of a complicated combination and interaction of leakage line plumes and a two dimensional, vertical surface, wall (door) plume. The results and conclusions of 3.3.3.2 would again be relevant.

3.3.4 A Summary of the Test Method's Shortcomings

As a result of the above investigation the following shortcomings of the DP 5925 test method have been identified.

A. The net rate of outflow from the port of the enclosure is a result of two, unknown, time-varying and inseparable components, namely, actual leakage from the furnace and enclosure gas expansion due to hot door surface heat transfer. In general these two components can be of the same order of magnitude.

B. The time to approach quasi-steady-state conditions within the enclosure (subsequent to vent closing) will depend on the door surface temperature and on the door assembly leakage characteristics. In contrast to the suggestion of section 7.3 of DP 5925, this time will not generally be less than 1 minute. For example, in the present NBS/UL tests even 2 minutes was not generally ample for the development of quasi-steady conditions. In this regard, the situation would have been even worse if the door had been specifically designed for "tightness" and/or it had been insulated.

C. Assuming that a quasi-steady-state condition is reached within the enclosure at a reasonably short time following vent closure (e.g., within a time short enough so that the unexposed side of the door assembly was not subjected to inordinate heating

by hot enclosure gases), 1) the velocity distribution in the outflow port cross section will be highly nonuniform with zero velocity occurring somewhere in the lower half; 2) a one point velocity measurement for estimating the net (leakage plus expansion) port outflow can lead to significant errors; and, 3) the vertical distribution of furnace to enclosure pressure differential may be significantly different from that distribution maintained during the open vent portions of the test. For example, if the door sill pressure difference is maintained at zero during the open vent phase, then it will not be zero during the closed vent phase. As a result of this overall variation in pressure distribution, the total leakage flow rate across the assembly can vary significantly depending on whether an open or closed vent condition prevails.

In view of these shortcomings it appears that the DP 5925 test method will not yield reliable estimates for the desired leakage characteristics which it sets out to measure.

4. AN ALTERNATIVE TEST CONCEPT

4.1 The Alternative Test Concept and Its Overall Advantages

This section will introduce an alternate test method concept for measuring door assembly leakage characteristics. The test method has neither the limitations discussed in section 3.2, nor the shortcomings described in section 3.3. While requiring reasonably steady furnace operating conditions, it does not require furnace pressurization. The test concept represents a universal test method in the sense that a single door assembly test setup could lead to leakage data at low, moderate and high furnace (room of fire origin) temperature and under conditions ranging from small to large pressure differentials.

A sketch of the proposed test concept is presented in figure 19. Various features of this concept are noted on this figure and the most significant ones are discussed below.

4.2 Significant Features of the Test Concept

4.2.1 Continuous Quasi-Steady Operation

The most important feature of the test concept is the fact that it involves a continuously quasi-steady operating procedure. Thus, to a good approximation and at all times during the course of the test, steady-state mass balance can be correctly applied to the enclosure. In particular, $\dot{m}_{leak}$, the rate at which furnace gases leak past the door assembly, can be computed from

$$\dot{m}_{leak} = \dot{m}_{exit} - \dot{m}_{in} \qquad (11)$$

where, as indicated in figure 19, $\dot{m}_{exit}$ and $\dot{m}_{in}$ are the measured mass rates of gas flow into and out of the enclosure.

4.2.2 Accurate Simulation of Ambient Conditions

In order for the test to provide a reasonably accurate simulation of the door assembly response to a real fire scenario, the temperature history of the unexposed surface of the assembly must be properly simulated. This temperature history will, of course, depend on the history of the rate of heat transfer from the assembly surface. But the rate of heat transfer is controlled by the ambient conditions. Thus, simulation of the door assembly response requires simulation, in the enclosure, of the significant features of typical adjacent room ambient conditions.

Independent of any specific door assembly of interest and independent of the pressure difference across it, the ambient condition characteristics which will lead to an appropriate simulation of the desired heat transfer are 1) maintaining the enclosure surfaces at room temperature, and 2) maintaining zero to low velocity room temperature air at positions away from the immediate vicinity of the door surface. The first of these characteristics is to ensure simulation of radiant energy exchange between the hot door surface and the cool bounding surfaces of an adjacent (to room of fire origin) space. The second of these characteristics is to ensure simulation of natural convection heat transfer from an elevated temperature door surface to a (relatively) quiescent, ambient temperature, adjacent room atmosphere.

With regard to the second of the above characteristics, low velocity is intended to mean a velocity which is, at most, characteristic of normal room draft velocities. It is also intended to mean a velocity that is small relative to characteristic velocities in the convective door surface boundary layer at times when convective heat transfer becomes significant. In general, air velocities of the order of 0.1 m/sec or less will satisfy the low velocity criteria. Thus, for the present purposes, no significant variation in convective heat transfer is anticipated if the ambient velocities vary with this range. As will be seen, the allowable flexibility (0 - 0.1 m/sec) in upward air velocity would be taken advantage of in the design of enclosure ventilation control.

As indicated in figure 19, both of the above ambient condition characteristics are a design feature of the enclosure test fixture. Enclosure surfaces are maintained near room temperature by forced cooling, either air (from fans on the outside) or water. The enclosure environment is continuously and slowly flushed from bottom to top by clean, cool, low velocity air.

Besides performing the prime function of door assembly heat transfer simulation, cool operating conditions for the enclosure structure would lead to its general endurance and long life.

4.2.3 Universal Control of the Furnace-to-Enclosure Pressure Differential

The proposed test method is conceived in a manner as to permit continuous and precise control of the furnace-to-enclosure pressure differential during the entire course of a test, and this without any adjustment or control of furnace pressure. As indicated in figure 19, this pressure control is accomplished by varying the flow resistance of the upper fan-duct system. The control would be done either manually or automatically and in a manner as to continuously maintain the enclosure pressure (i.e., the furnace-to-enclosure pressure differential) at any desired value.

Assume, for example, that one wished to study leakage resulting from a configuration where the elevation of the neutral plane is at the door sill (as is the objective of the DP 5925 Part 3 test method). Then, throughout the course of the test, the upper duct valve would be continuously adjusted in a manner as to maintain this pressure differential condition. (Valve adjustments would definitely be required as the door assembly leakage characteristics were altered due to continued fire exposure.) Alternatively, by a proper (large) opening of the valve, the enclosure pressure could be easily maintained at a negative pressure relative to ambient. In this manner, a relatively large furnace-to-enclosure pressure differential could be imposed across the door assembly, thereby simulating the characteristic, high-rise building over-pressure phenomenology discussed in section 2.

By proper component selection, the lower fan-duct-flowmeter system at the enclosure inlet would be designed so that the mass flow rate of air passing into the enclosure would be relatively insensitive to the above-mentioned variations of enclosure pressure. That this can be easily achieved is evident from the following observations. First notice that the enclosure pressure would always be required to stay within the bounds, say,

$$-0.4\,\text{in}_w < P_{encl} - P_{amb} < 0$$
$$-100\ \text{Pa} < P_{encl} - P_{amb} < 0$$

Now assume that the lower flowmeter and duct is designed so that the fan delivers a desired rate of inlet air, $\dot{m}_{in}$, from the ambient while overcoming a pressure drop of, say, 5 to 10 in_w = 1250 to 2500 pascals. If P_{encl} is maintained within the above relatively narrow range, it is evident that with the use of such ventilation components the mass rate of air actually delivered to the enclosure would vary by a relatively small amount from the design $\dot{m}_{in}$ value. As noted in the previous paragraph, moderate variations in the mass rate of air flow (i.e., in the upward enclosure air velocity) do not upset the desired simulation of the door assembly response.

In view of all the above, it is evident that, with proper design the single upper valve actually provides both rapid response and universal control of the furnace-to-enclosure pressure differential. The significant implication of all this is contained in

the following summary conclusion:

A device of this design is capable of providing a predetermined, rapid response furnace-to-enclosure pressure differential during the course of a standard, door assembly fire endurance test. With such a capability, a total evaluation of the subject door assembly leakage characteristics could be obtained.

4.2.4 Accuracy of the Leakage Measurement

Having described the basic test concept and some of the rationale for the design of the test enclosure, attention is again refocused on the basic measurement of $\dot{m}_{leak}$. This is embodied in eq. (11). Thus, the accuracy of determining $\dot{m}_{leak}$ at any instant of time is dependent on the accuracy of measuring $\dot{m}_{exit} - \dot{m}_{in}$.

Within reasonable limits, the basic test configuration is such as to permit $\dot{m}_{exit}$ and $\dot{m}_{in}$ measurements of any desired accuracy. The key to this capability lies in the fact that the pressure drop in both the upper and lower flowmeter-duct systems can be designed to be arbitrarily large. (Whatever the magnitude of the desired pressure drop, an appropriate fan would be selected to overcome it.) With the availability of a large pressure drop, an appropriate flowmeter (and associated pressure measuring instrumentation) can be selected which would provide any reasonable desired degree of accuracy in the measurement of the mass flow rates.

5. SUMMARY

This investigation of the measurement of door assembly smoke leakage has been presented in four major sections.

In the first section a basis for relating overall intrabuilding smoke migration dynamics to high temperature compartment partition smoke leakage measurements was formulated. The approach taken was to develop the concept of smoke compartmentation, and to identify and discuss the implications of the two different smoke migration phenomena that would be in effect on each side — the fire side and the protected side — of the leaking compartment partition.

The second section presented the results of applying the tentative, high temperature ISO test method DP 5925. This test method was designed to measure the smoke leakage of door assemblies during the course of a standard fire exposure. As was seen, these results led to unanswered questions regarding the validity of the test method. In order to answer these questions, further testing and an in-depth analysis of the test method was carried out. The results of the further testing were reported in section 2.

The analysis of the DP 5925 Part 3 test method was presented in the third section. As concluded in section 3.2, the basic test method as written was found to be limited in practice. In particular, the test objective, even if attained, would not result in a clear evaluation of the performance of door assemblies during fire scenarios where standard, high-rise building, stack effects come into play.

Perhaps more significantly, serious theoretical problems with the test and its procedures were identified in section 3.3. Taken all together, these latter problems led to the following conclusion: For door assemblies where enclosure gas temperatures during quasi-steady conditions do not approach the level of furnace temperatures, and where such quasi-steady conditions are attained within a few minutes of vent closure, the basic DP 5925 Part 3 test method can potentially yield rough estimates for the desired smoke leakage characteristics which it sets out to measure. However, to accomplish this, significant additional data would have to be acquired. For example, once quasi-steady conditions prevail, the net enclosure outflow could be estimated from figure 17 once the elevation of the neutral plane (i.e., the position of zero velocity) within an outflow duct cross section and the temperature of the enclosure gas near the general vicinity of this elevation was determined.

An alternate test concept has been formulated which removes the limitation and theoretical problems of the DP 5925 Part 3 test method. This concept was presented in figure 19 and in section 4 wherein several of its significant features were identified and briefly discussed. The concept holds promise as a universal type of test method in the sense that a single door assembly setup would lead to reliable leakage data throughout the entire course of a fire endurance test, and under conditions ranging from small to large pressure differentials. Moreover, the test concept is not restricted only to the evaluation of door assembly leakage characteristics. Indeed, it could also be used to evaluate the leakage characteristics of overall wall and floor assemblies. In short, it is strongly recommended that the alternate test concept be developed to the point where its apparent potential promise can be evaluated in a more tangible manner.

6. ACKNOWLEDGEMENTS

The author gratefully acknowledges Mr. Lionel A. Issen of Construction Fire Research, CFR/NBS who provided all liaison between UL and NBS during the course of the test program and who transmitted and decoded all of the data that was acquired. Also acknowledged are those members of the UL staff, notably Mr. Robert M. Berhinig, Engineering Group Leader, who carried out the tests described herein with the flexibility that was required by nature of the task at hand.

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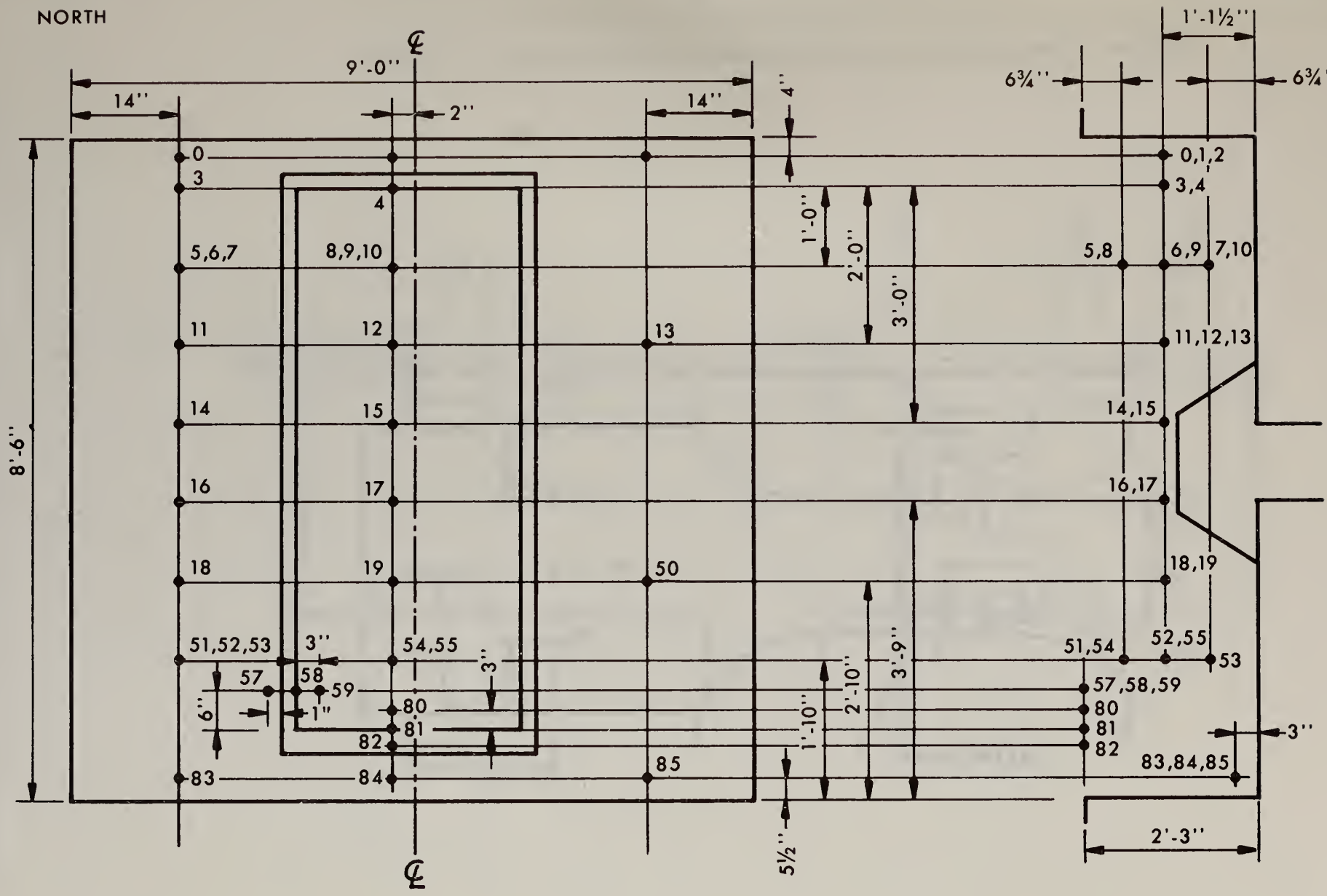


Figure 1. Location of thermocouples in the enclosure

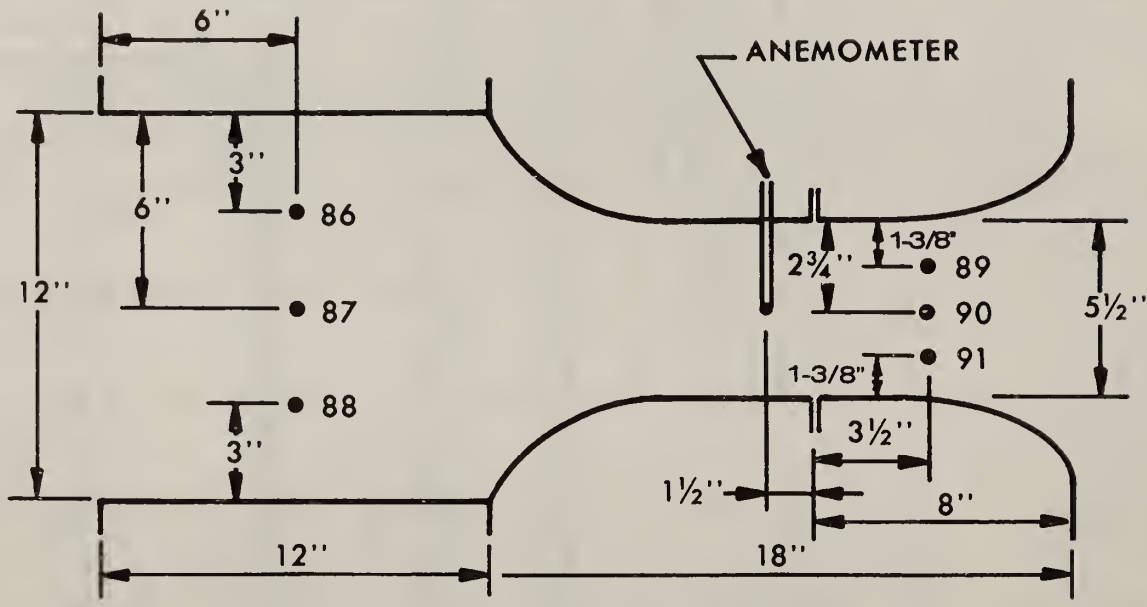


Figure 2. Location of thermocouples in the enclosure outlet

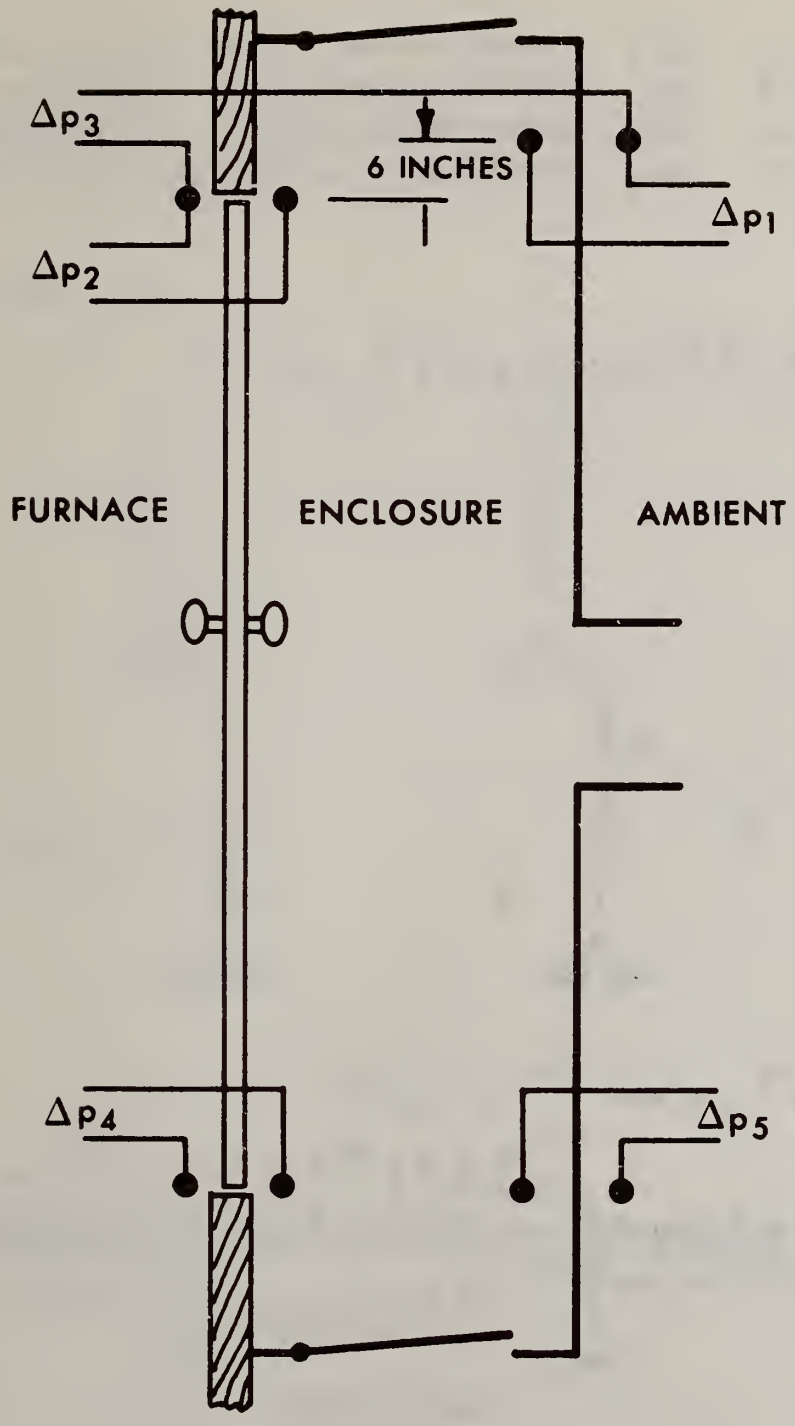


Figure 3. Location of pressure differential measurements

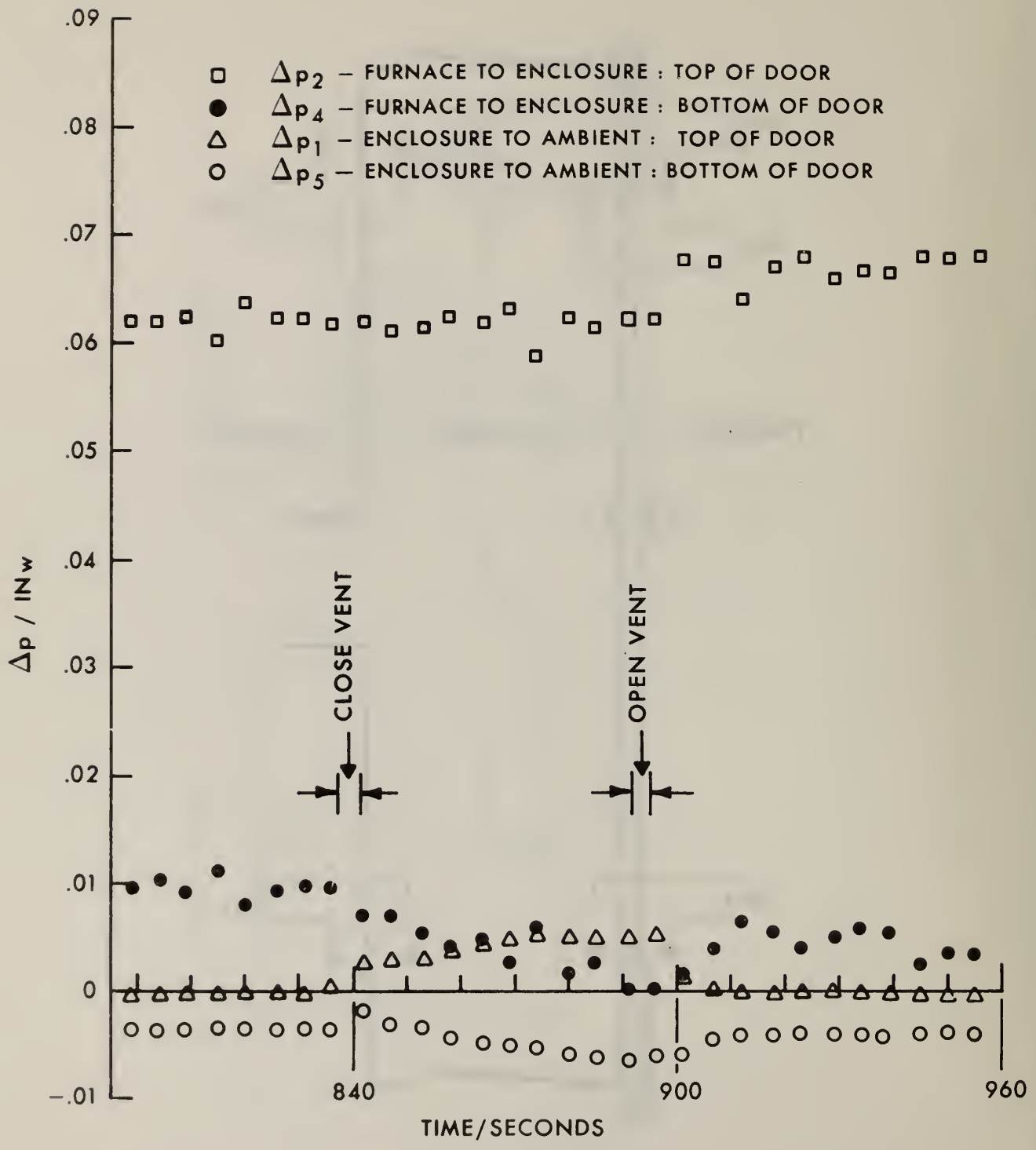
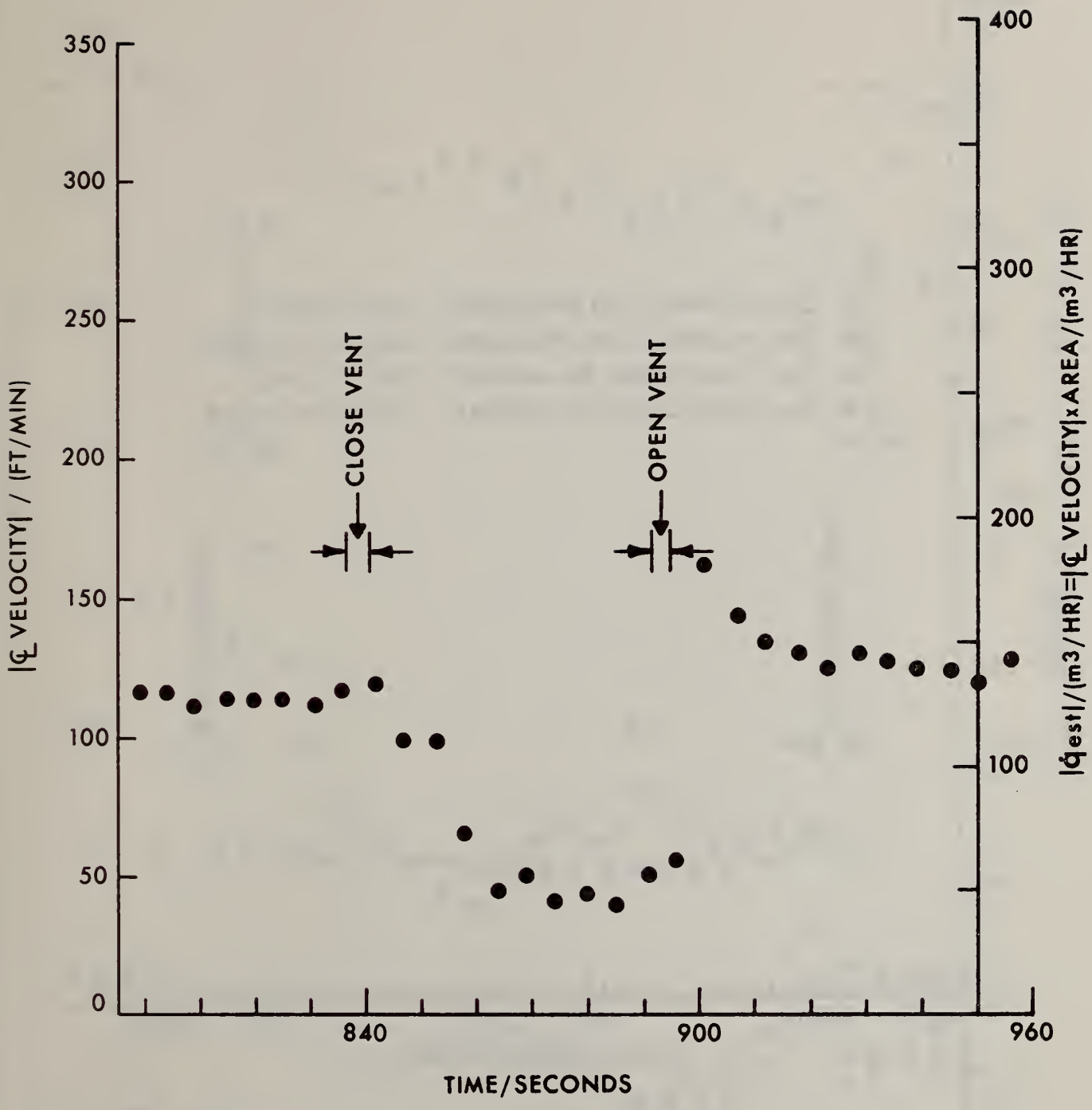


Figure 4. Various ΔP's during 840-900-second closed vent interval



tflow velocity during 840-900-second closed vent interval

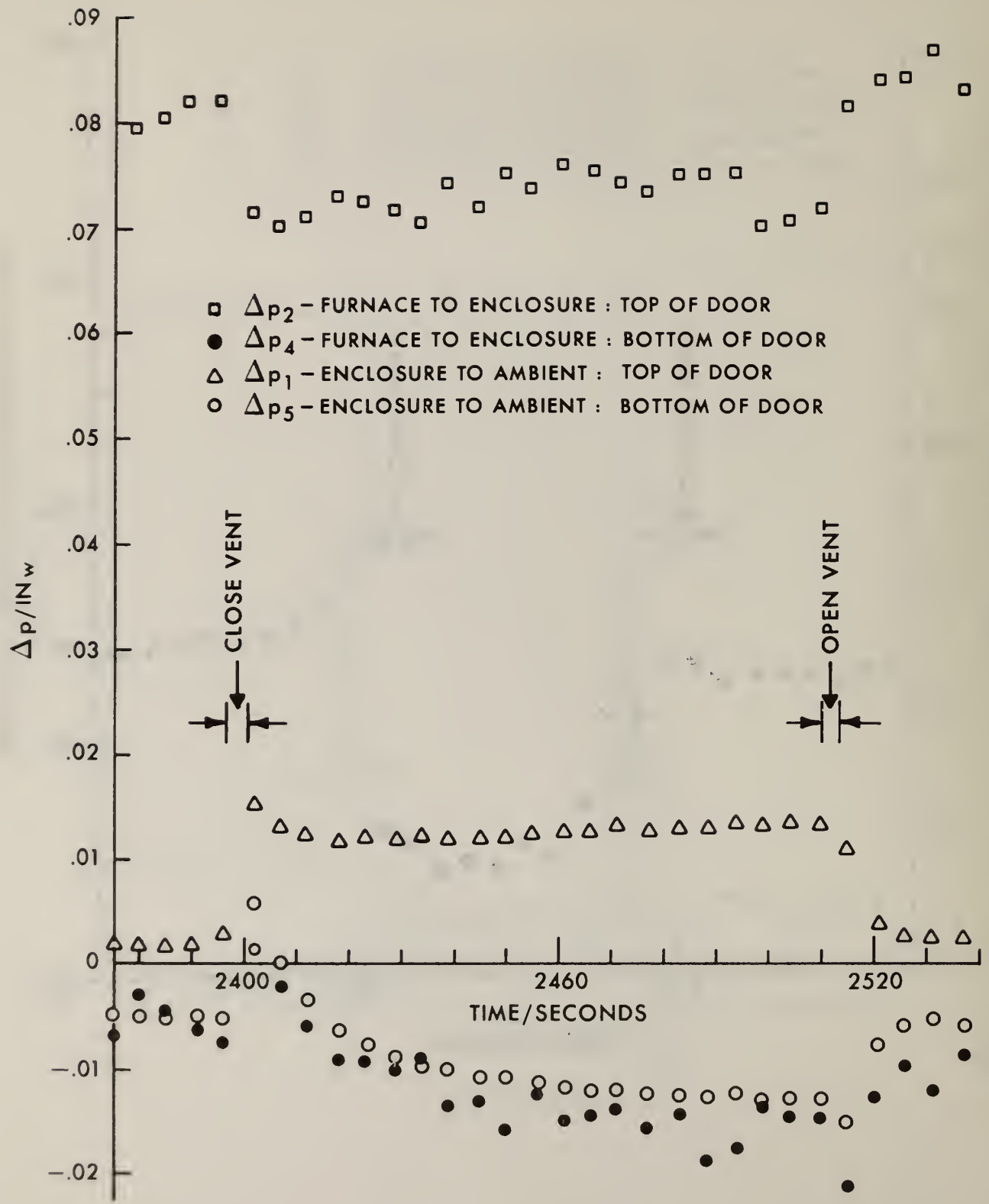


Figure 6. Various ΔP's during 2400-2520-second closed vent interval

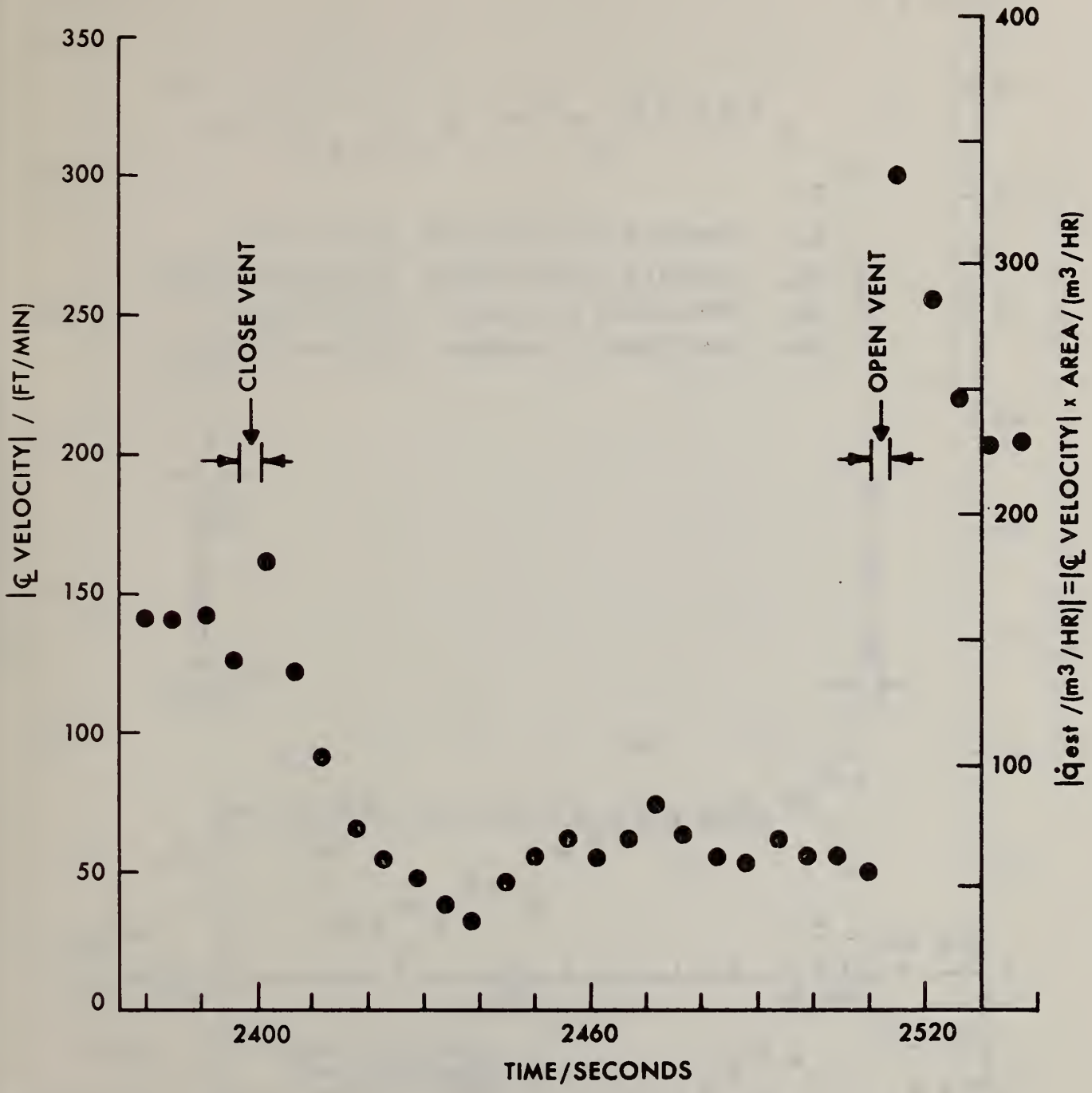


Figure 7. Outflow velocity during 2400-2520-second closed vent interval

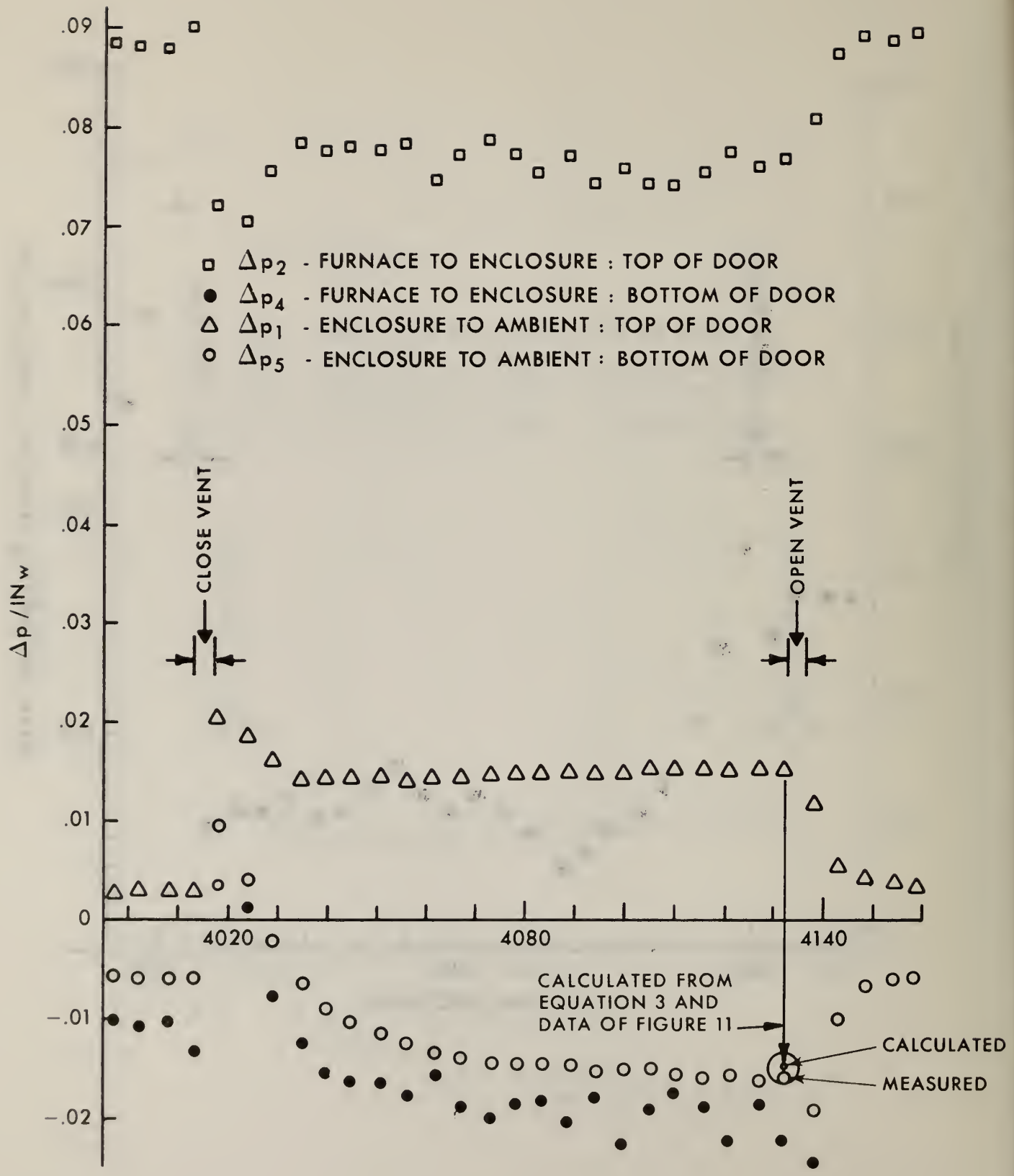


Figure 8. Various ΔP's during 4020-4140-second closed vent interval

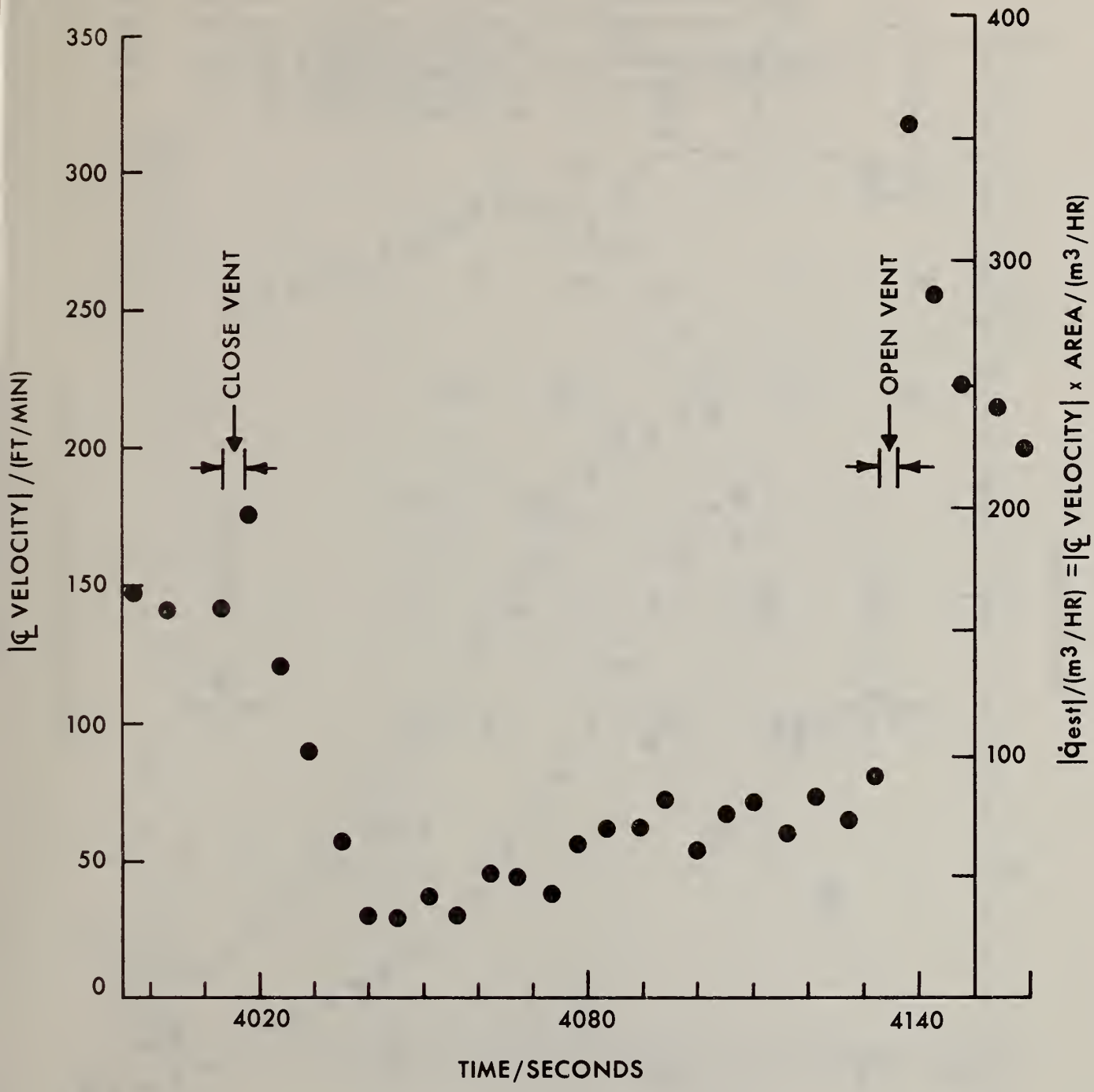


Figure 9. Outflow velocity during 4020-4140-second closed vent interval

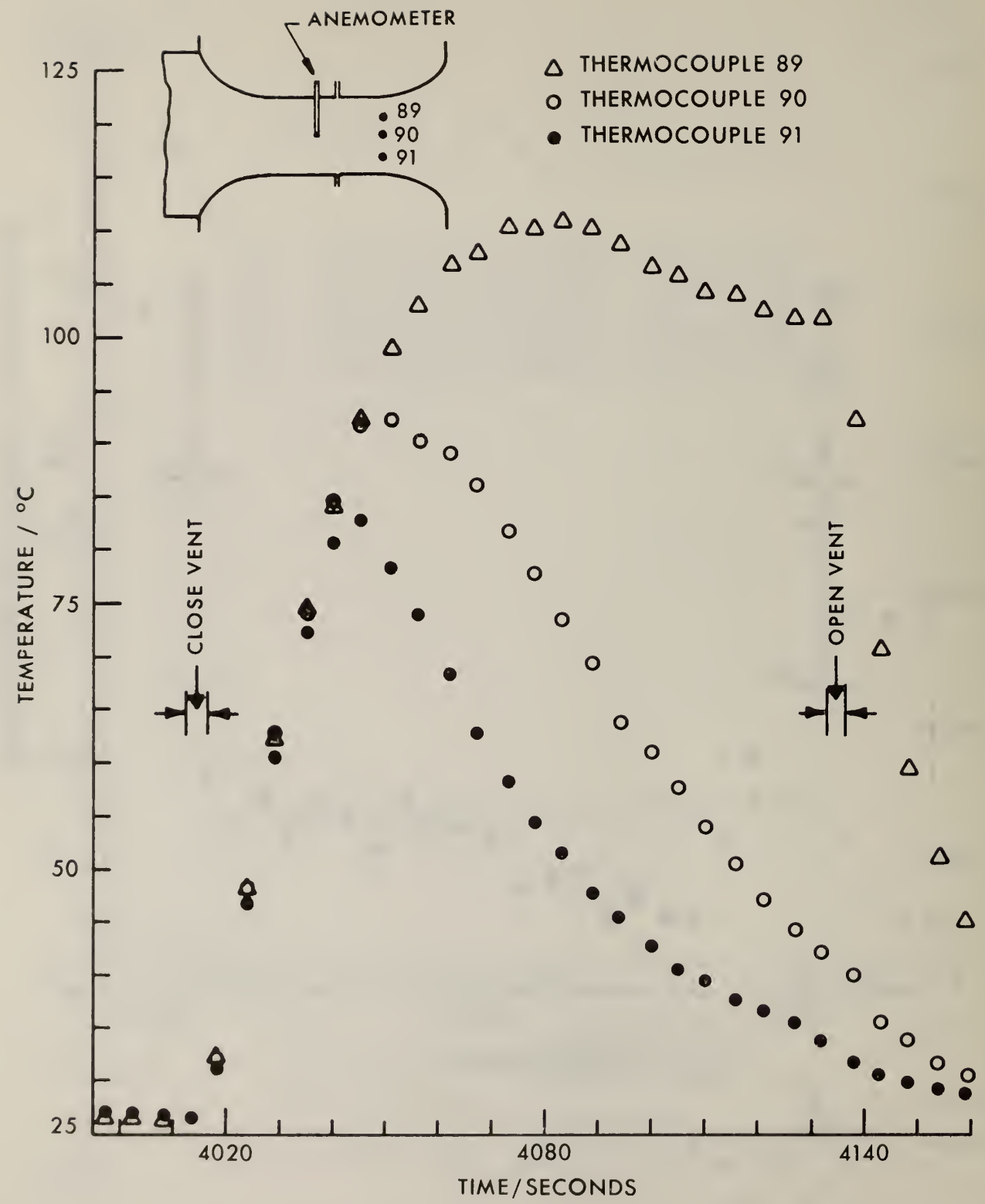


Figure 10. Venturi throat thermocouple temperatures during 4020-4140-second closed vent interval

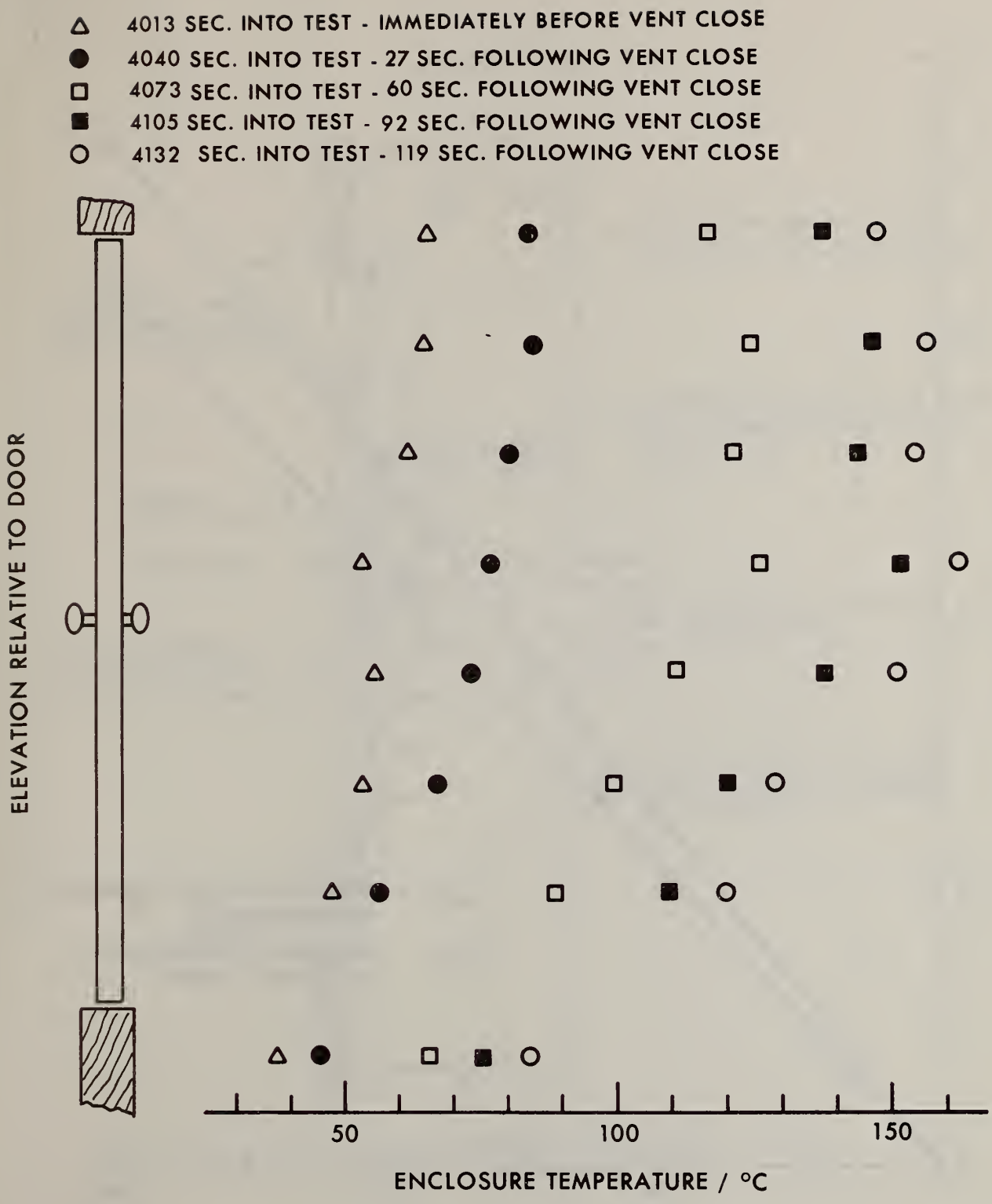

△ 4013 SEC. INTO TEST - IMMEDIATELY BEFORE VENT CLOSE
● 4040 SEC. INTO TEST - 27 SEC. FOLLOWING VENT CLOSE
□ 4073 SEC. INTO TEST - 60 SEC. FOLLOWING VENT CLOSE
■ 4105 SEC. INTO TEST - 92 SEC. FOLLOWING VENT CLOSE
○ 4132 SEC. INTO TEST - 119 SEC. FOLLOWING VENT CLOSE
ELEVATION RELATIVE TO DOOR
50
100
150
ENCLOSURE TEMPERATURE / °C

Figure 11. Enclosure temperature as a function of elevation during the 4020-4140-second closed vent interval

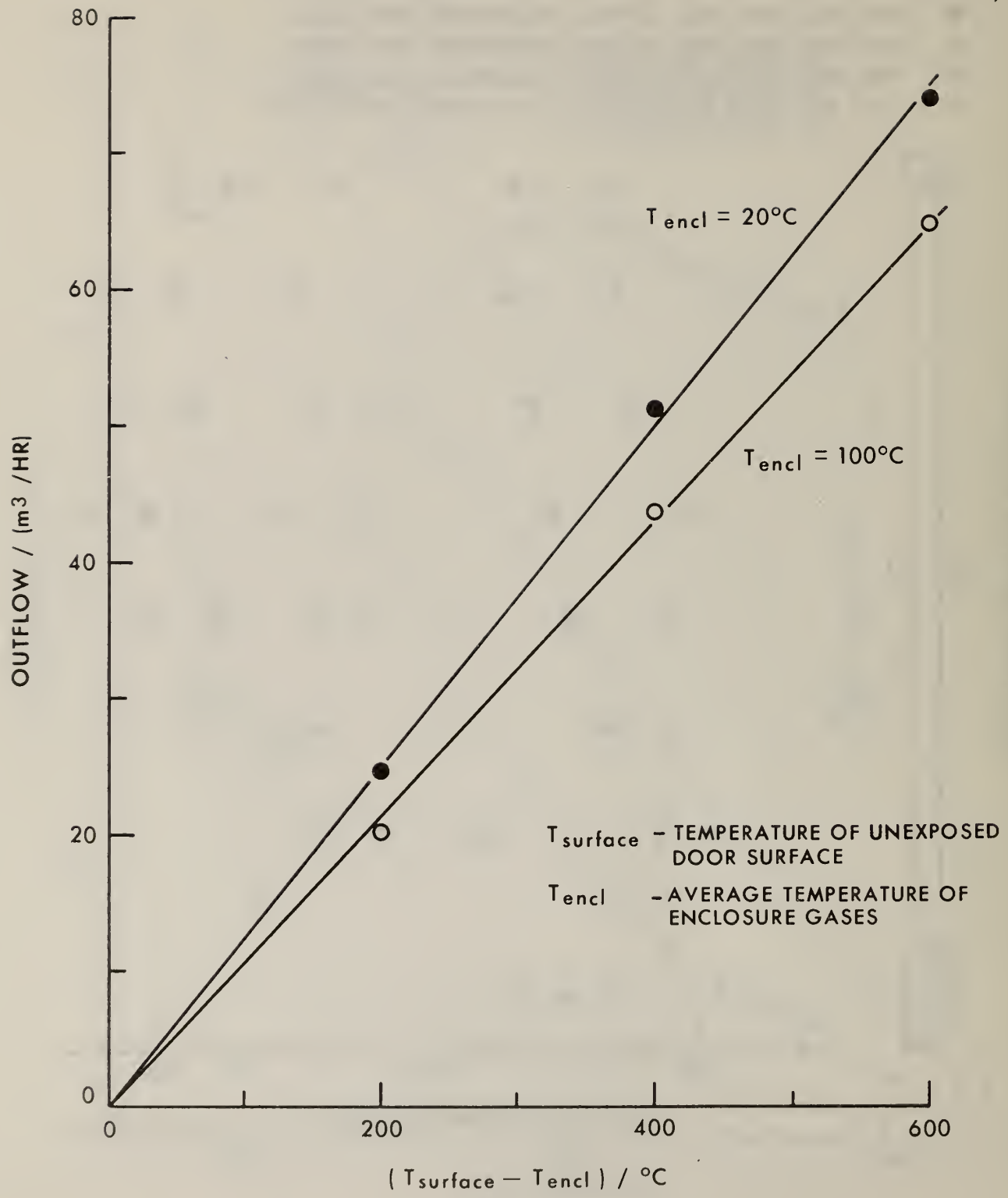


Figure 12. Estimates of outflow due solely to expansion for a door of dimension 1 m x 2 m

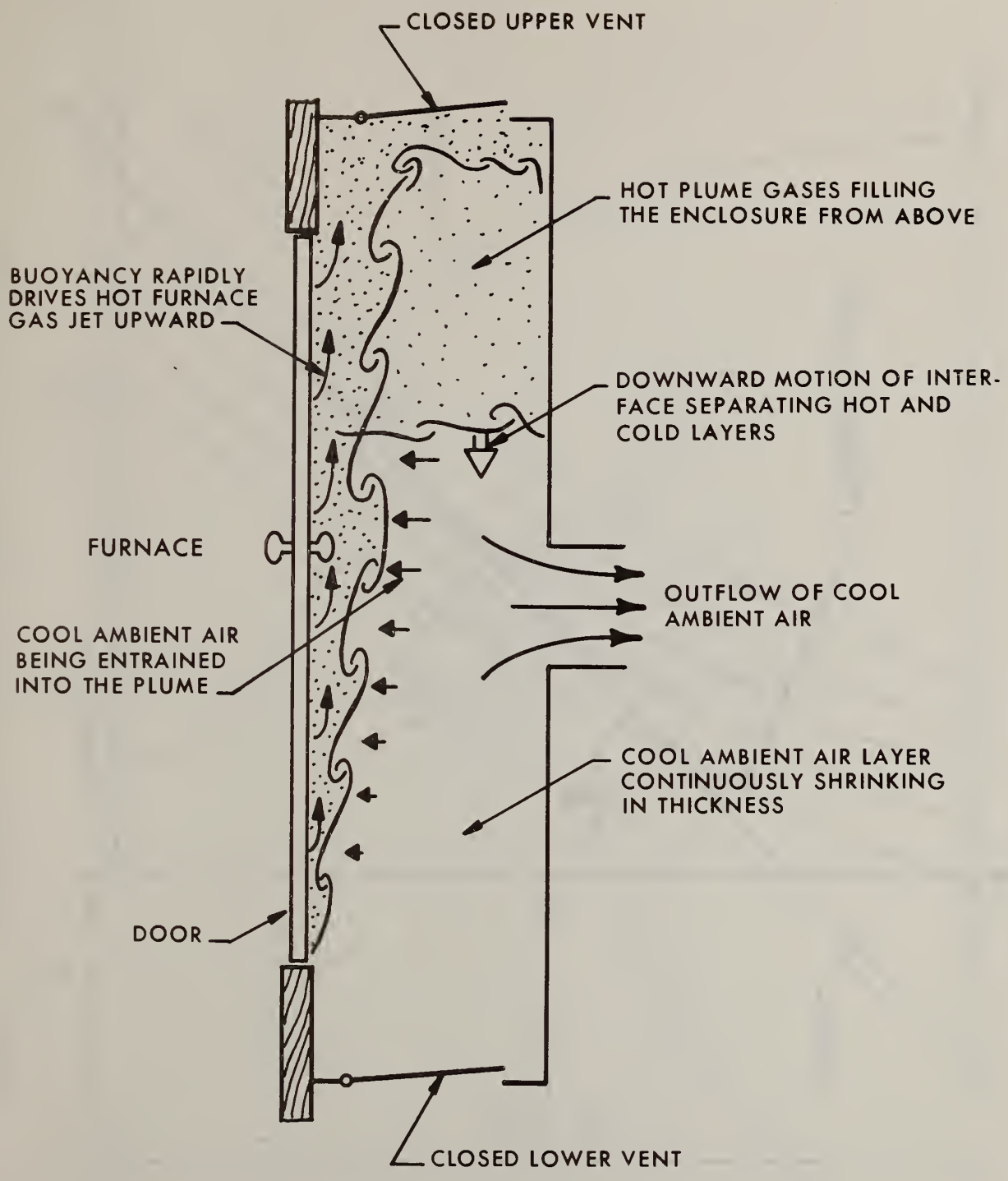

CLOSED UPPER VENT
HOT PLUME GASES FILLING THE ENCLOSURE FROM ABOVE
BUOYANCY RAPIDLY DRIVES HOT FURNACE GAS JET UPWARD
DOWNWARD MOTION OF INTER-FACE SEPARATING HOT AND COLD LAYERS
FURNACE
OUTFLOW OF COOL AMBIENT AIR
COOL AMBIENT AIR BEING ENTRAINED INTO THE PLUME
COOL AMBIENT AIR LAYER CONTINUOUSLY SHRINKING IN THICKNESS
DOOR
CLOSED LOWER VENT

Figure 13. Idealized model of flow within the enclosure shortly after vent closure

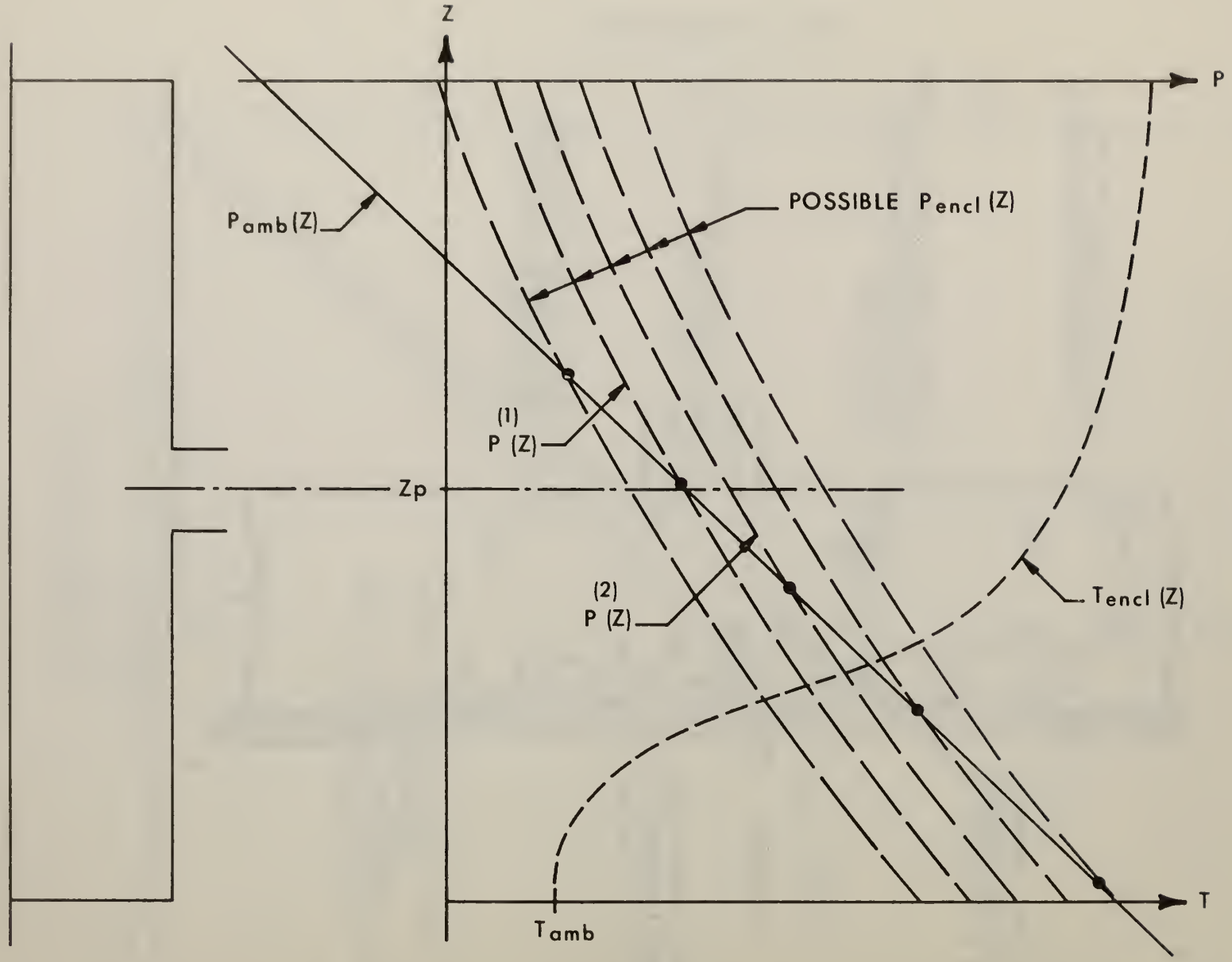


Figure 14. A sketch of a vertical distribution of enclosure temperature and plots of possible resulting distributions of enclosure pressure

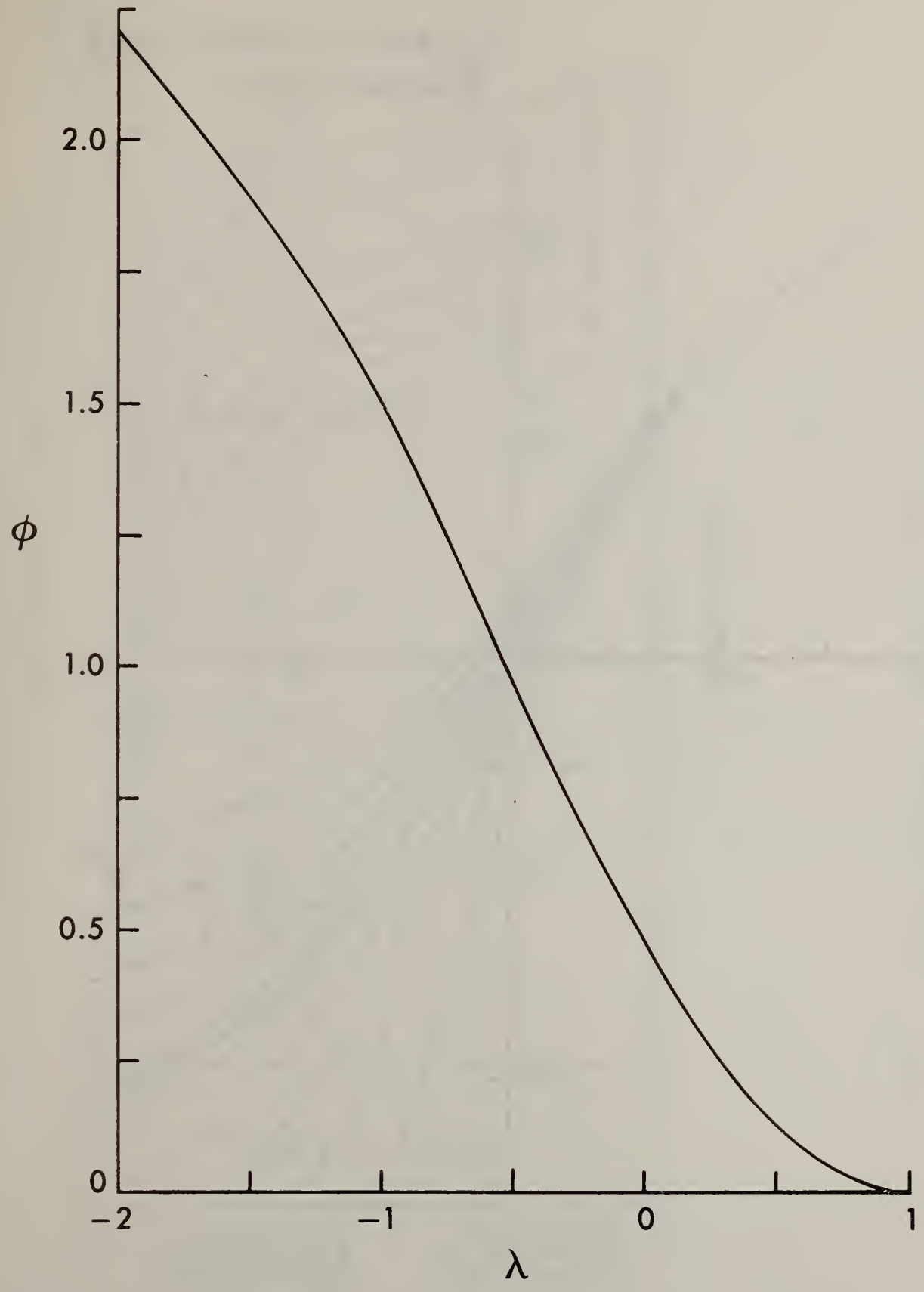


Figure 15. Plot of $\phi(\lambda)$ defined in eq. (9)

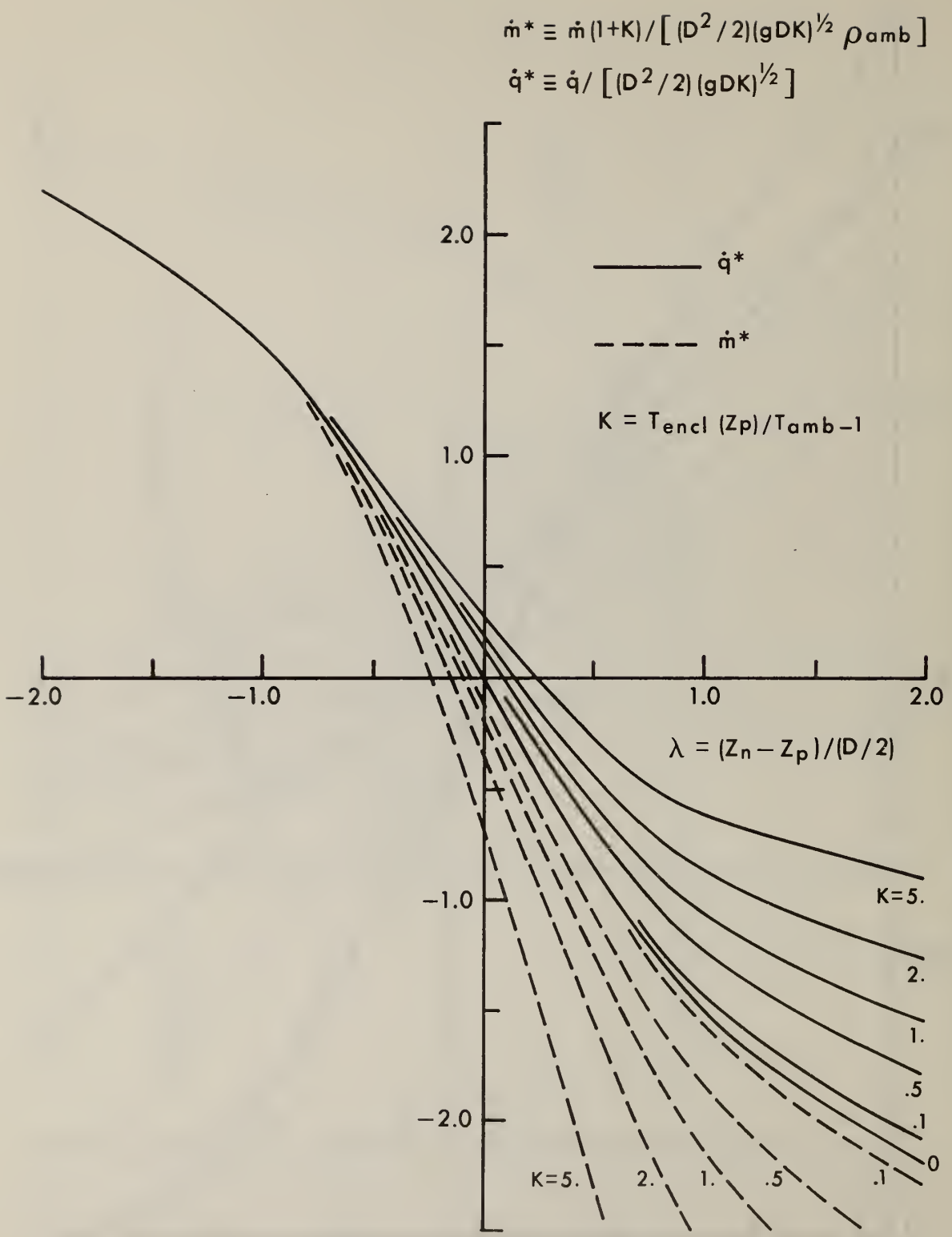


Figure 16. Plots of $\dot{m}^*$ and $\dot{q}^*$ as functions of λ with K as a parameter. See eq. (9).

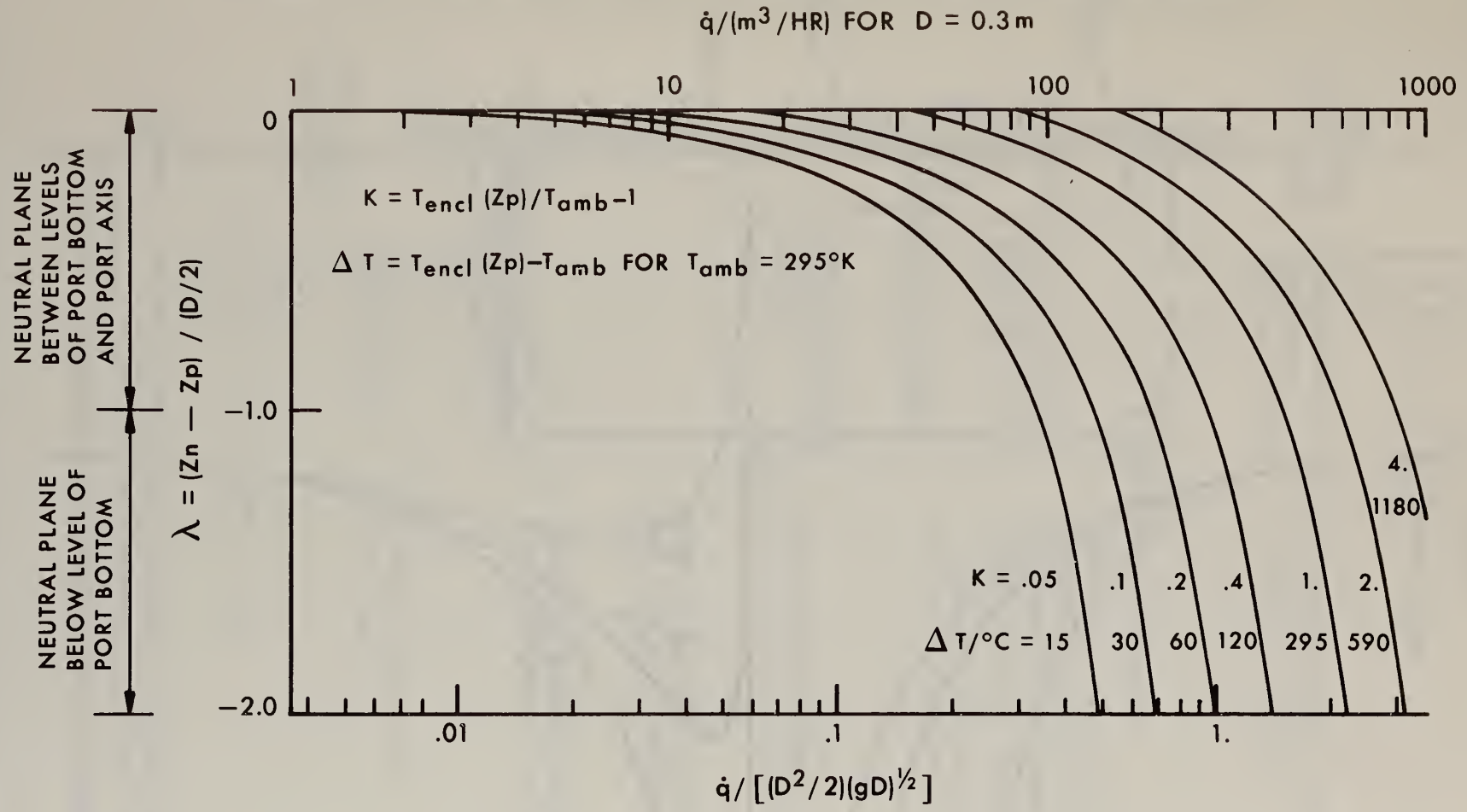


Figure 17. Plot of $\dot{q}/[(D^2/2)(gD)^{1/2}]$ as a function of λ with K as a parameter. Plot of $\dot{q}$ as a function of λ with ΔT as a parameter, for D = 0.3 m and T_{amb} = 295°K.

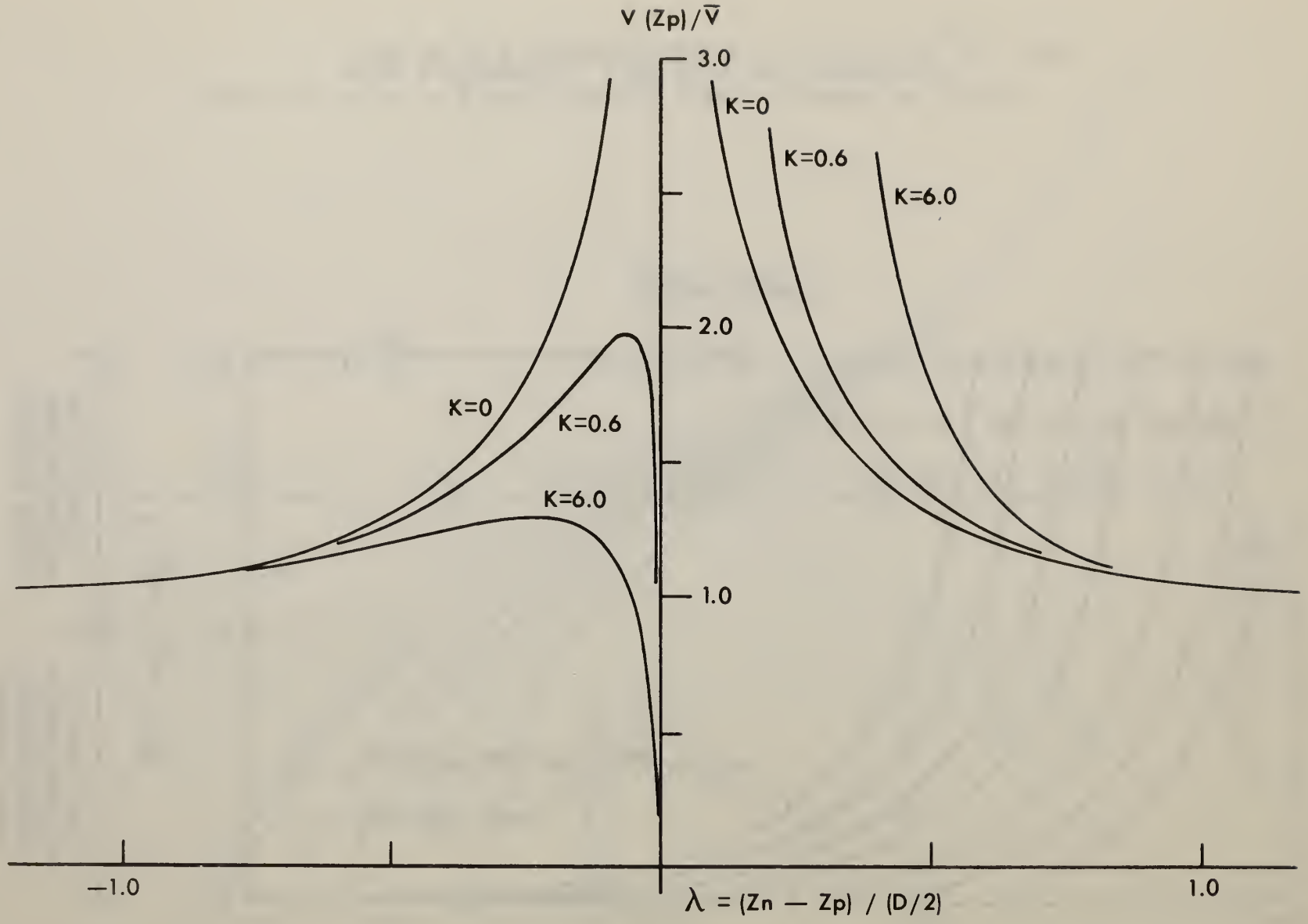


Figure 18. Plot of $V(Z_p)/\bar{V}$ as a function of λ with K as a parameter

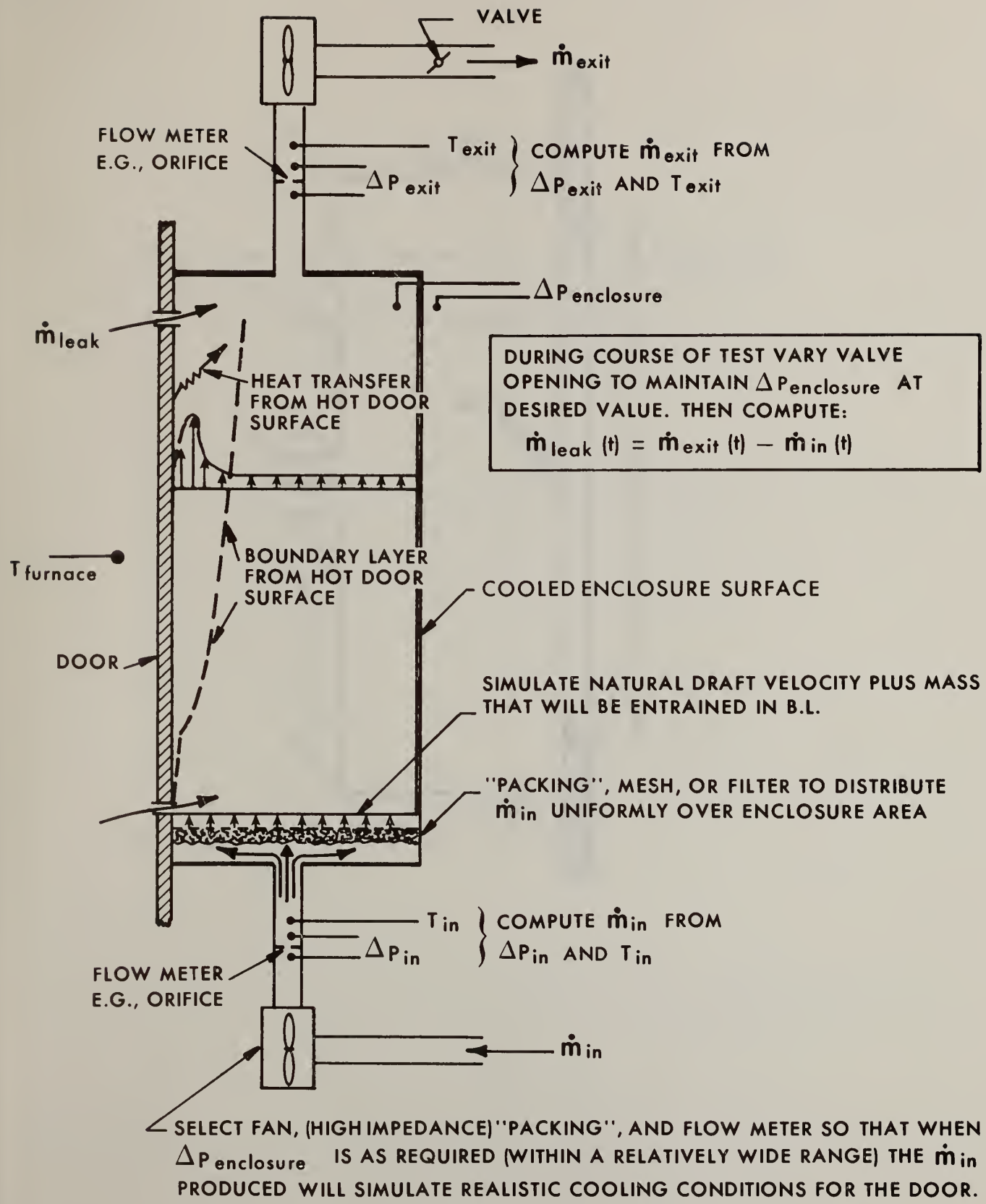

VALVE
$\dot{m}_{exit}$
FLOW METER
E.G., ORIFICE
T_{exit}
ΔP_{exit}
COMPUTE $\dot{m}_{exit}$ FROM
ΔP_{exit} AND T_{exit}
$\Delta P_{enclosure}$
$\dot{m}_{leak}$
DURING COURSE OF TEST VARY VALVE OPENING TO MAINTAIN $\Delta P_{enclosure}$ AT DESIRED VALUE. THEN COMPUTE:
$\dot{m}_{leak}(t) = \dot{m}_{exit}(t) - \dot{m}_{in}(t)$
HEAT TRANSFER FROM HOT DOOR SURFACE
$T_{furnace}$
BOUNDARY LAYER FROM HOT DOOR SURFACE
COOLED ENCLOSURE SURFACE
DOOR
SIMULATE NATURAL DRAFT VELOCITY PLUS MASS THAT WILL BE ENTRAINED IN B.L.
"PACKING", MESH, OR FILTER TO DISTRIBUTE $\dot{m}_{in}$ UNIFORMLY OVER ENCLOSURE AREA
T_{in}
ΔP_{in}
COMPUTE $\dot{m}_{in}$ FROM
ΔP_{in} AND T_{in}
FLOW METER
E.G., ORIFICE
$\dot{m}_{in}$
SELECT FAN, (HIGH IMPEDANCE) "PACKING", AND FLOW METER SO THAT WHEN $\Delta P_{enclosure}$ IS AS REQUIRED (WITHIN A RELATIVELY WIDE RANGE) THE $\dot{m}_{in}$ PRODUCED WILL SIMULATE REALISTIC COOLING CONDITIONS FOR THE DOOR.

Figure 19. A test concept for measuring leakage of door assemblies during standard fire endurance tests

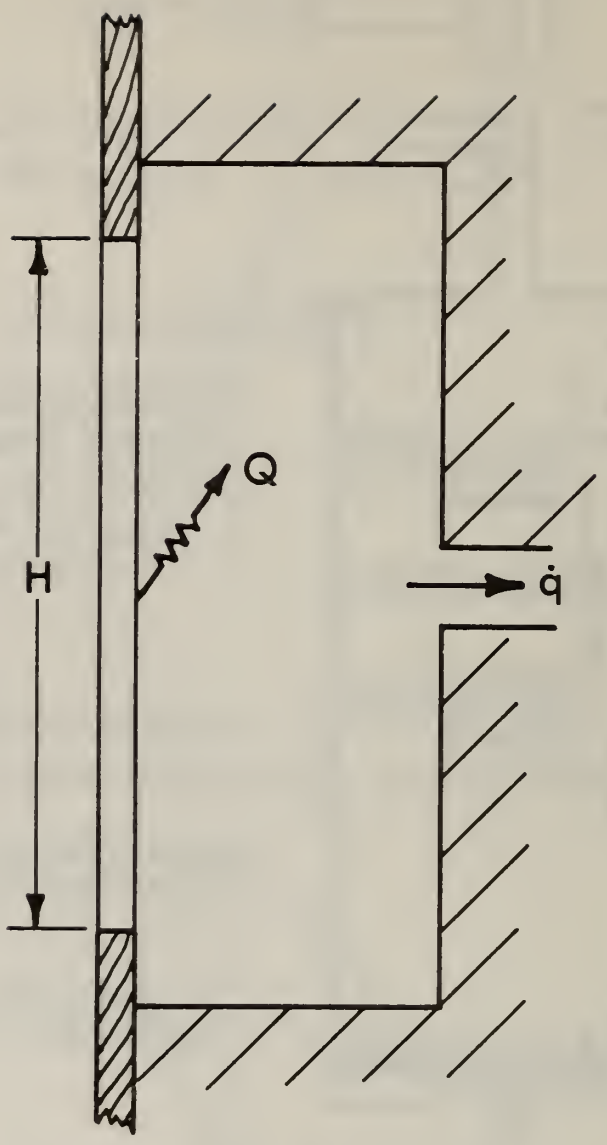


Figure 20. Model for determining the rate of outflow, $\dot{q}$, which is associated solely with the heat transfer rate, Q

APPENDIX A

ISO/TC 92/WG 3 N 203. DP 5925 FIRE TESTS -- SMOKE CONTROL DOOR ASSEMBLIES. PART 3. HIGH TEMPERATURE TEST (REVISION OF DOCUMENT N 189)

Document No:- ISO/TC 92/WG 3 N 203
June 1978

ISO INTERNATIONAL ORGANIZATION FOR STANDARDIZATION
ORGANISATION INTERNATIONALE DE NORMALISATION

ISO/TC 92/WG 3 Fire resistance doors shutters and glazed elements (of TC 92 Fire tests on building materials and structures

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DP 5925 FIRE TESTS - SMOKE CONTROL DOOR ASSEMBLIES
PART 3. HIGH TEMPERATURE TEST (Revision of document N 189)

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FOREWORD

(The first Part of the foreword is prepared by ISO Central Secretariat giving details of the member bodies which approved the proposal.)

This standard method of test is one of a series being prepared by ISO/TC 92 'Fire tests on building materials and structures' for the assessment and evaluation of the performance of door assemblies intended to act as barriers to smoke in fire.

The severity of the heat exposure and test conditions governs the smoke control performance of doors and has led to the preparation of the standard in Parts. Further explanations and guidance on this and other considerations are given in DP 5925: Part 0. Laboratories are advised to acquaint themselves with the contents of the commentary before using any of the tests in this series.

This standard specifies a method of testing and evaluating the performance of door and shutter assemblies intended to act as barriers to smoke under high temperature conditions. The test is designed to be carried out using the same furnace and generally under the conditions of the test specified in ISO 3008[1]. It does not, however, adopt the same pressure conditions as ISO 3008, and some aspects of the ISO 3008 test (e.g. cotton pad test) are omitted. Further tests in the series are being prepared as follows:

DP 5925 Fire tests - Smoke control door assemblies
Part 1. Ambient temperature test.

DP 5925 Fire tests - Smoke control door assemblies
Part 2. Medium temperature test.

NOTE - So that suitable precautions to safeguard health of test personnel may be taken, the attention of all concerned fire tests is drawn to the possibility that toxic or harmful gases may be evolved in combustion of test elements.

1. SCOPE AND FIELD OF APPLICATION

This International Standard specifies a method of testing and evaluating the performance of door assemblies including rolling shutter and other closure assemblies intended to control the passage of smoke in conditions of high temperature. This test measures the flow of air through the test assembly at one pressure level.

This test procedure does not provide a means of determining criteria to ISO 3008 nor mechanical damage to a door assembly, and these should be assessed separately.

---

1) ISO 3008 Fire resistance test, door and shutter assemblies.

2. DEFINITIONS

For the purpose of this International Standard, the definitions given in ISO 1804[1], ISO 3261[2] and DP 5925: Part 0 together with the following are applicable:

2.1 door assembly (doorset): An assembly including a fixed part (the door frame), one or more movable parts (the door leaves) and their hardware, the function of which is to allow or to prevent access.

2.2 smoke control door: A door assembly whose primary function is to resist the passage of smoke as determined by DP 5925.

2.3 high temperature: A temperature representative of a fully develped fire according to the standard temperature time as specified in ISO 834[3].

3. TEST PRINCIPLE

In a building fire, there will generally be an increase in pressure on the exposed face of a door inducing smoke to be transmitted from the high to the low pressure side of the door. At high temperatures, not only will there be an increase in pressure but a pressure gradient will develop over the height of the door and the severity of the exposure conditions may cause some doors to suffer damage and distortion increasing the size of gaps through which smoke can pass.

The test procedure exposes a door to the heating conditions specified in the standard fire-resistance test (ISO 834) and simulates standard pressure conditions. Provision is made for the collection and measurement of the rate of flow and temperature of hot gases passing from the high to the low pressure side of the door.

4. APPARATUS

4.1 Furnace

The furnace shall be capable of subjecting one side of the specimen to the heating and pressure conditions specified in ISO 834.

Means shall be provided for increasing and maintaining the pressure conditions within the furnace to those required by 7.3.2.

---

1) ISO 1804 Doors terminology.

2) ISO 3261 Fire tests, vocabulary.

3) ISO 834 Fire resistance tests - elements of building construction.

4.2 Enclosure

The enclosure (see figures 1 and 2) shall comprise the following[1]):

a) A light metal frame shall be clad with thin metal sheet (for example approximately 1.5 mm thick).

b) All faces of the enclosure shall have a non-reflective black finish.

c) Glazed inspection panels shall be provided as necessary.

d) Closable vents shall be provided in the top and bottom, having an area as large as is possible. If required, additional vents may be provided. The design of the vent shall not allow leakage under test conditions.

e) Handles shall be provided on the vent shutters together with a mechanism to enable simultaneous closing.

f) The overall dimensions shall be appropriate to allow it to be firmly fixed to the wall in which the door assembly is installed and to completely cover the exposed face. The depth shall be between 600 mm and 700 mm.

g) A circular opening, of diameter 300 $\pm$ 5 mm, shall be provided at mid-height in the back face of the enclosure to which a shaft of 300 $\pm$ 10 mm in length and circular cross section shall be attached to accommodate the thermocouple and anemometer.

h) A sheet metal radiation shield with reflective surfaces for the protection of the anemometer with a diameter 450 $\pm$ 10 mm shall be attached to the underside of the box with straps at 250 $\pm$ 10 mm from the back.

4.3 Method of attachment of enclosure to furnace surround

When a door is to be tested in a wall surround made of material containing free moisture, the inside of the enclosure shall be sealed from the concrete surround by means of copper foil (see figure 3) or by other acceptable methods to prevent moisture from the concrete entering the enclosure. The foil shall be cemented at the corners to eliminate air leaks.

The enclosure shall normally[2]) be attached to the furnace surround by means of thick steel angle sections as shown in figure 3. However, this does not preclude the use of other suitable methods if desired.

---

1)
Working drawings will be available from the secretariat of ISO/TC 92 at the time of publication.

2)
An alternative method of fixing may be necessary for testing double doors.

4.4 Instrumentation

4.4.1 Thermocouple

A thermocouple shall be located in the axis of the measuring shaft to measure the temperature of the gases approaching the anemometer. Additional thermocouples may be used at other points in the enclosure.

4.4.2 Pressure measuring equipment

The measurements of pressure to an accuracy of ± 1 Pa shall be made at a minimum of three positions located along a verical axis on one side of and close to the door assembly in line with the top and bottom edges of the door opening and at one third of the height from the sill level (see ISO 3008, 7.1).

4.4.3 Anemometer

A high temperature anemometer shall be fitted in a venturi tube as shown in figure 1. This shall be capable of measuring gas flows from 20 m^3/h to 750 m^3/h at temperatures up to 120 °C, and within a velocity range of 0.2 m/s to 20 m/s.

5. PREPARATION OF TEST SPECIMENS

5.1 Construction[1)]

The test shall be performed on a complete door assembly as intended to be used in practice, incorporating all hardware and other equipment[2)]. The finish and form of the specimen shall be representative of the finish and form of the door as installed in its intended position of use.

The mounting of the test specimen shall be representative of its use in practice so that appropriate clearances exist between door and its frame.

When the specimen is tested in a surround[3)] intended for the determination of fire-resistance the requirements of ISO 3008, 5.2 shall also apply.

---

1)
See ISO 3008, page 1, note 3.

2)
The performance of a door assembly is influenced by the mechanical features of construction. The results of a fire test may not always be valid for a construction having overall dimensions larger or much smaller than those of the test specimen (see DP 5925: Part 0).

3)
During the development of the test the specimens should be mounted in a concrete surround other materials may be used provided that adequate sealing can be ensured.

5.2 Conditioning

Specimens containing hygroscopic materials or other materials which can be affected by moisture shall be conditioned to equilibrium with the prevailing conditions in the laboratory which shall be within the following limits:

temperature (dry bulb)	298 ± 15 °K
relative humidity	40 % to 65 %

Doors or shutters made entirely of metal or of metal and glass do not require conditioning.

6. CALIBRATION

In phase one of the calibration, the gas flow rate, (m3/h), through the test door assembly shall be measured at ambient temperature when a pressure differential, ΔP_0(Pa), exists between the test furnace and the enclosure (see figure 4). The pressure differential between the enclosure and the test laboratory shall be small when compared with ΔP_0(Pa). If the flow rate is too small, the door can be opened a little and if it is too large, the door can be sealed with tape.

In phase two of the calibration, the measurement opening in the enclosure shall be tightly sealed. The pressure in the furnace shall be increased and the pressure differentials between the furnace and the enclosure, ΔP_1(Pa), and between the enclosure and the test laboratory, ΔP_2(Pa), shall be measured.

The tightness of the enclosure, K, shall be calculated from the formula

$$k = \sqrt{\frac{\Delta P_1}{\Delta P_0 \Delta P_2}}\ Q$$

where: Q = gas flow rate (m3/h)

and shall not exceed the value of unity.

7. PROCEDURE

7.1 Mounting and preparatory routine

7.1.1 For a full assessment, tests shall be performed on two specimens by exposing opposing faces to the furnace; this may be done simultaneously or separately, depending on the equipment available1).

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1) To meet special circumstances or if it can be ascertained by observation that the leakage through the door from one side to the other from the one direction is likely to be significantly higher than from the other, the testing authority may decide to test a single assembly with the direction of air flow from this one direction only.

7.1.2 Prior to fixing the enclosure, the door shall be opened and closed at least ten times to check the adequacy of the opening arrangements. A door equipped with an automatic closing device shall be allowed to close by means of this device[1].

7.1.3 The enclosure shall be attached to the furnace surround in accordance with 4.3.

7.1.4 The air leakage rate of the enclosure shall be determined according to clause 6.

7.2 Test conditions

7.2.1 The door shall be subjected to the heating conditions required by ISO 3008.

7.2.2 A positive pressure gradient shall be applied in accordance with ISO 3008, but shall be adjusted so that the pressure difference in the range zero to +1 Pa exists at the bottom of the test specimen.

7.3 Operating procedure

The test shall be started with the vents open. After 4 min, the vents shall be closed and the pressure differential regulated to the specified value. A period of 1 min shall then be allowed for conditions within the enclosure to stabilize. At the end of this period, the following shall be recorded:

a) the pressure at top and bottom of the door;

b) the temperature in the enclosure;

c) the temperature of the hot gases within the measuring shaft;

d) the flow rate of the hot gases.

The vents shall be reopended and the procedure repeated at intervals of 5 minutes.

7.4 Test duration

The test shall be terminated

a) when the specimen no longer meets the criteria under which the performance is being judged; or

b) when the operational limits for the measuring system are exceeded[2];

---

1) This procedure is not intended to be a durability test representing the wear and tear normally found in use.

2) For the type of instruments used in the development of the test the limits were found to be at a temperature not greater than 311 °C or at a gas flow rate not greater than 750 m³/h.

c) at a time mutually agreed between the sponsor and the testing laboratory

8. TEST RESULTS

The temperatures and rates of flow of hot gases (m^3/h) at time intervals as specified in 7.3 shall be recorded in tabular form.

9. TEST REPORT

The test report shall include the following information:

a) name of testing laboratory;

b) name of sponsor;

c) date of test;

d) name of manufacturer and trade-name (if any) of product;

e) details of the construction, physical characteristics and conditioning of the specimen together with drawings; clearances and gaps between the door and frame shall be fully recorded;

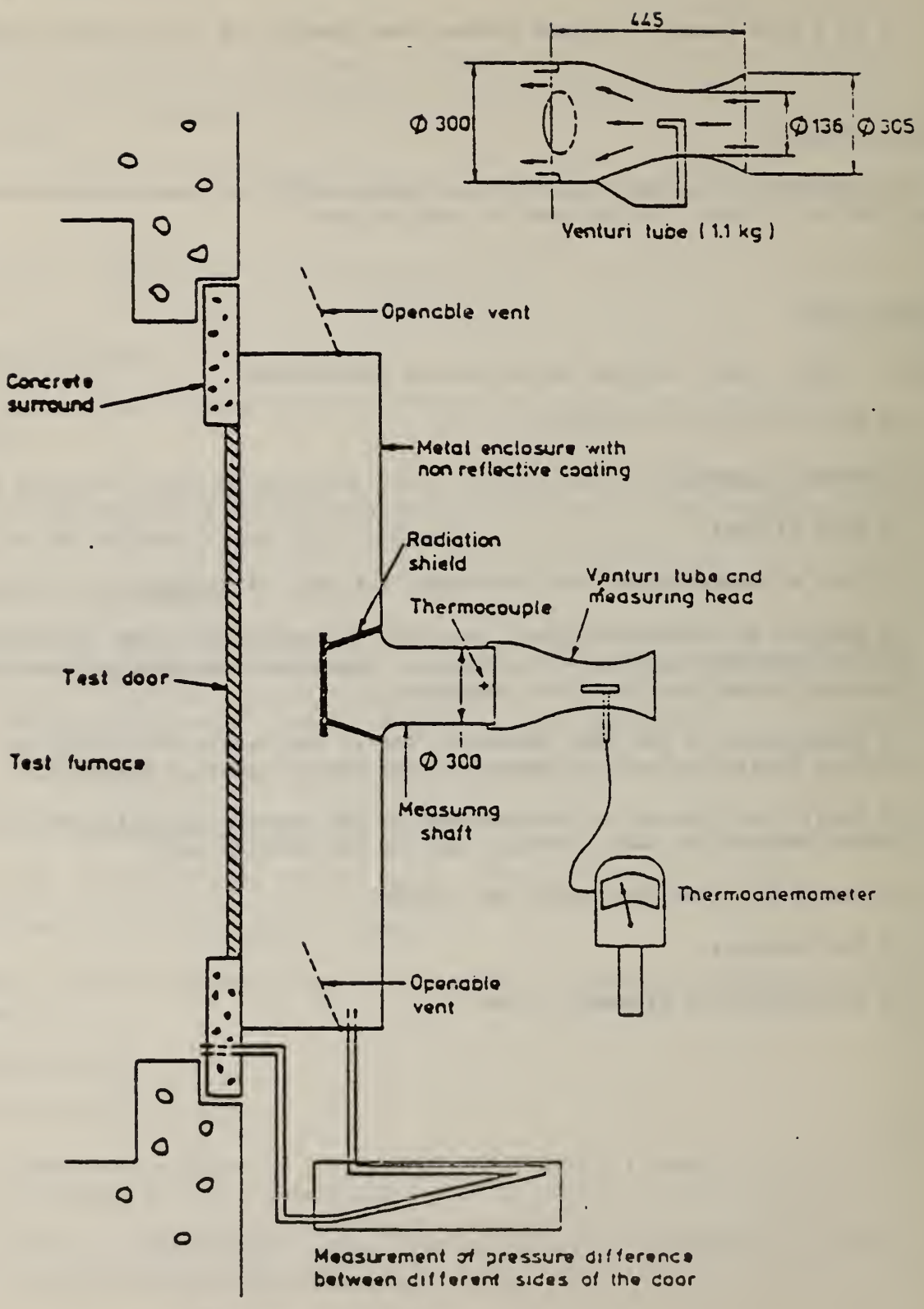
f) description of the test apparatus and if applicable the direction of the heating conditions with reference to the door or shutter assembly;

g) details of fixings of the specimen to the surrounding wall and of any joints between the door assembly and the surrounding wall;

h) the side of the door which was tested;

j) test results;

k) description of glazing, if any.



All dimensions in millimetres

FIGURE 1. MEASUREMENT OF AIR LEAKAGE DURING A HIGH TEMPERATURE TEST

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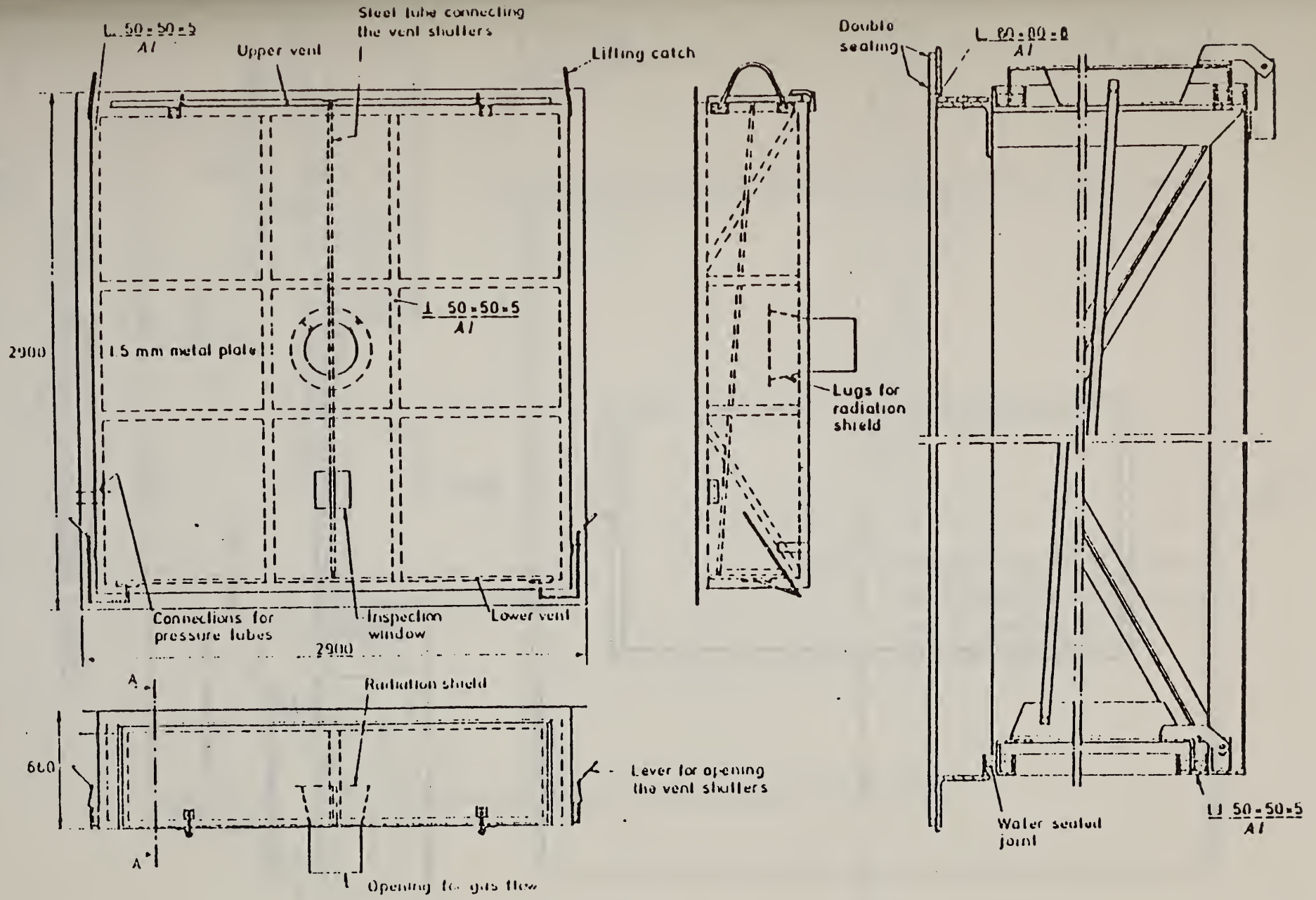
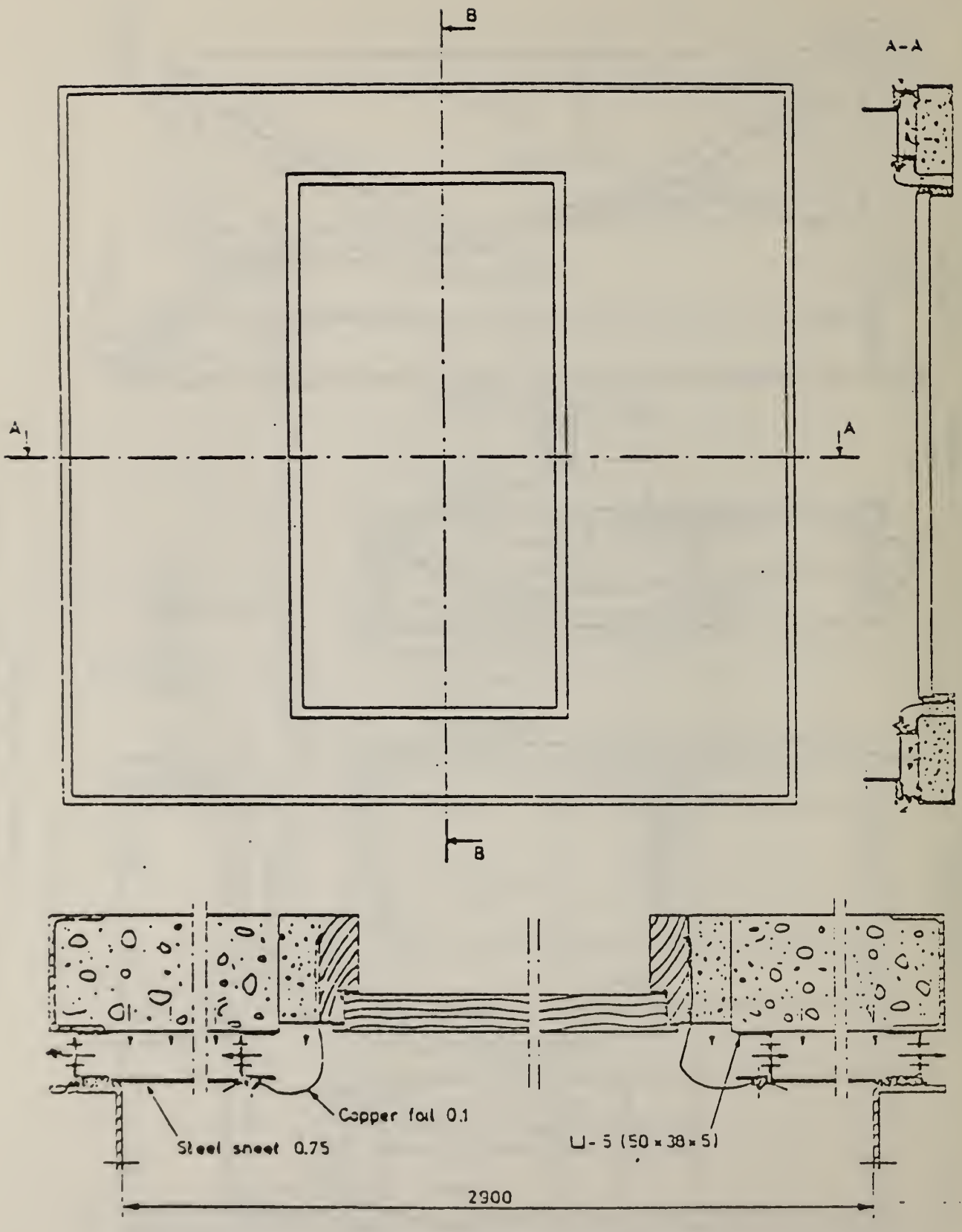


All dimensions in millimetres

FIGURE 2 : ENCLOSURE FOR LEAKAGE RATE MEASUREMENT



All dimensions in millimetres

FIGURE 3. ENCLOSURE AND FURNACE SURROUND

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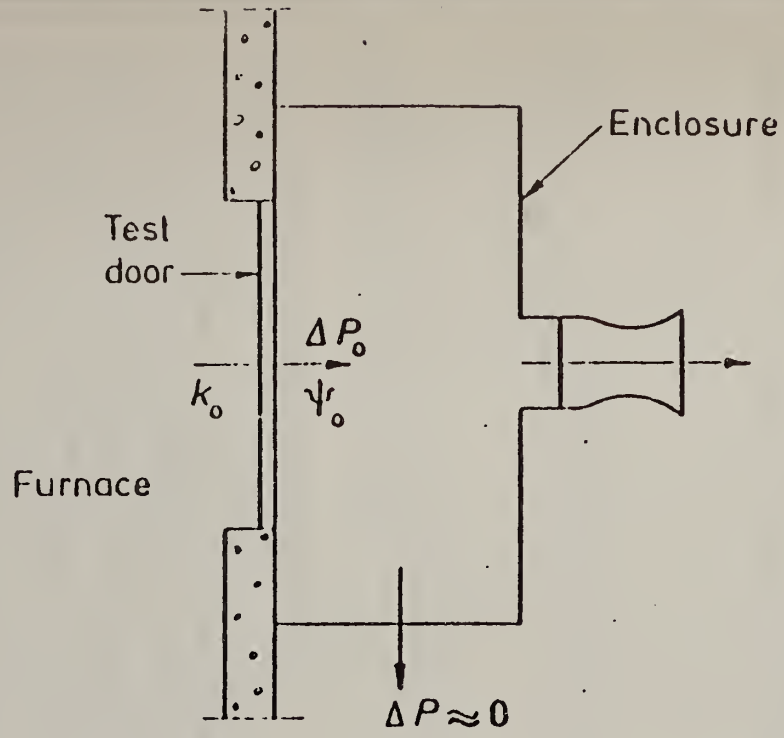
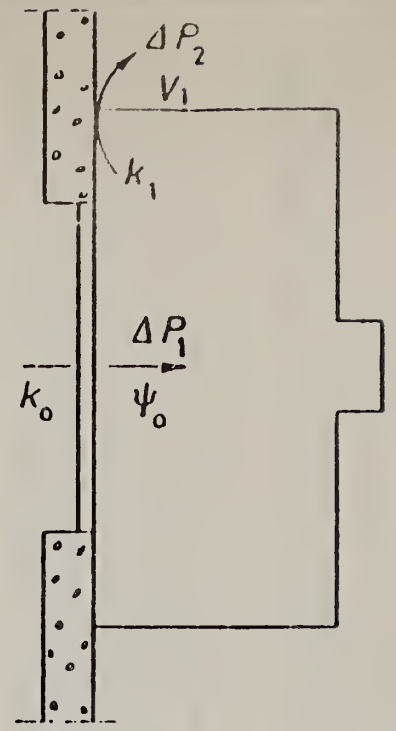


Phase 1. Gas flow measurement at ambient temperature



Phase 2. Measurement of pressure differentials with measurement opening in the enclosure closed

FIGURE 4. CALIBRATION OF ENCLOSURE (SEE CLAUSE 6)

DRG NO. 14 570 / 4

APPENDIX B

AN ESTIMATE OF THE RATE OF GAS OUTFLOW DUE TO HEAT TRANSFER FROM THE DOOR SURFACE

B1. THE MODEL

The purpose of this appendix is to present an estimate of the order of magnitude of outflow that is to be anticipated solely as a result of heat transfer to and expansion of enclosure gases. We assume that the door assembly is without any leakage paths. We assume further that the unexposed (to the furnace) door surface is of height H and width W.

The simplest possible model of the phenomenology under study is depicted in figure 20. Here we have assumed that all significant heat transfer, Q, to the enclosure gases is from the door surface. As a result of this energy input there is a net rate of expansion of gases in the enclosure, and some of the enclosure gases are pushed out of the single opening at a volumetric outflow rate, $\dot{q}$, to be determined.

B2. THE RELATIONSHIP OF RATE OF OUTFLOW TO RATE OF HEAT TRANSFER

In reference [6] Zukowski has presented a result for heat addition to gases in a fixed volume enclosure with leaks. This is directly and generally applicable to our present model. Thus, assuming uniform exit gas (air) properties,

$$\rho_e \dot{q} C_p T_e = \dot{Q} \qquad \text{(B-1)}$$

where ρ_e, T_e, and C_p are the density, absolute temperature and specific heat at constant pressure, respectively, of the air which is actually exiting from the enclosure opening (i.e., from the "leak").

With a determination of the heat transfer rate, the desired outflow rate is immediately at hand by using the above result.

B3. AN ESTIMATE FOR THE HEAT TRANSFER RATE

For the purpose of estimating the heat transfer rate we assume that the door surface is at a uniform surface temperature, T_s, which is reasonably constant during a given closed vent phase of the test. We also assume that away from the door surface the temperature of the gases in the enclosure, T_{encl}, at a given instant of time is substantially uniform (e.g., $T_e = T_{encl}$).

The above assumptions and the outflow estimates to follow are very good all through the test at early times following vent closure. In fact, at such times $T_{encl} = T_{amb}$,

where T_{amb} is the ambient (laboratory) temperature. At later times following vent closure (e.g., at the approach of steady state), the uniform T_{encl} assumption may not be a particularly good one. However, even then the results below will provide a reasonable estimate of the order of magnitude of $\dot{q}$.

With the above in mind we consider convective cooling of the door surface by means of a buoyant, two dimensional, boundary layer which grows from zero thickness at the bottom of door*. This boundary layer will be entirely laminar, (mostly) turbulent, or in a transitional state, along the height of the door depending on whether [12]

$$\begin{aligned} &Gr\ Pr < 10^8 \text{ - laminar} \\ &10^8 < Gr\ Pr < 10^{10} \text{ - transitional} \\ &10^{10} < Gr\ Pr \text{ - mostly turbulent} \end{aligned} \tag{B-2}$$

where

Gr = Grashoft number = $g\ \beta\ (T_s - T_g)H^3/\nu^2$

Pr = Prandtl number = $C_p\ \mu/k$ (=.72 for air)

In these definitions for Gr and Pr, T_g is the temperature of the fluid outside the boundary layer and β, ν, μ, and k are characteristic values for the coefficient of thermal expansion, dynamic viscosity, viscosity, and thermal conductivity, respectively, of the fluid in the boundary layer.

For air, the average Nusselt number for the entire range of Gr can be computed from [12]

$$Nu_{ave} = h_{ave}H/k = \begin{cases} 0.511\ Gr^{1/4}; & Gr < 4.2\ (10^9) \\ 0.0184\ Gr^{2/5}; & 4.2\ (10^9) < Gr \end{cases} \tag{B-3}$$

where h_{ave} is the average heat transfer coefficient. In the above we will evaluate all the air properties, β, ν, μ, k, and C_p at the average boundary layer temperature $(T_s + T_{encl})/2$.

*Note that the effects of radiant heat transfer are not taken account of here. Radiant transfer from the hot door surface to the facing vertical enclosure surface would tend to maintain that latter surface at an elevated temperature. During the closed vent phases under consideration this hot surface would transfer additional energy to the enclosure gases thus yielding a net $\dot{q}$ which was larger than that to be computed.

Using the above results we can now compute the total heat transfer rate from

$$\dot{Q} = HWh_{ave} (T_s - T_{encl}) = Wk (T_s - T_{encl}) Nu_{ave} \qquad (B-4)$$

where Nu_{ave} is computed from eq. (B-3).

B4. THE RATE OF OUTFLOW

Using eqs. (B-1) and (B-4) we obtain our desired result

$$\dot{q} = Wk(T_s - T_{encl})/(\rho_{encl} T_{encl} C_p) \qquad (B-5)$$

$$= W \nu \beta (T_s - T_{encl}) Nu_{ave}/.72$$

In order to get actual estimates on $\dot{q}$ for our problem we have used this equation to estimate $\dot{q}$ as a function of $T_s - T_{encl}$ for a door of dimension H x W = 2 meters x 1 meter and for the two T_{encl} values 20°C, and 100°C. These results are presented in figure 12.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

A basis for relating overall intrabuilding smoke migration dynamics to high temperature, door assembly smoke leakage measurements is formulated. The results of applying the tentative, high temperature, ISO test method DP 5925 Part 3, which was developed to measure smoke leakage of door assemblies during the course of a standard fire endurance test, are reported. A critical analysis reveals that the basic objective of the method is limited in its utility in the sense that fire scenarios in high-rise buildings may not be adequately simulated. Consistent with the above-mentioned experimental results, troublesome theoretical problems with the test method and its procedures are identified. These lead to a conclusion that the test method as written is generally unreliable. An alternate test concept which removes the above-mentioned DP 5925 Part 3 limitation and all of its problems is described and its development is advocated.

17. KEY WORDS (six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)

Building fires; compartment fires; doors; egress; fire tests; high-rise buildings; leakage; life safety; smoke; smoke movement; stack effects; test methods.

18. AVAILABILITY

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